CHAPTER

19

Flexibility in the Development of Action

Karen E. Adolph, Amy S. Joh, John M. Franchak, Shaziela Ishak, *and* Simone V. Gill

Abstract

This chapter has two major aims. The first is to describe flexibility in motor action. Balance and locomotion in infants are used as a test case for understanding three aspects of behavioral flexibility—adaptive motor decisions, modification of ongoing activity, and new means to achieve a goal. The second aim is to illuminate the links between flexibility and development. In particular, it demonstrates that flexibility is acquired during development and that developmental changes both facilitate and impede its acquisition. It is shown that flexibility does not automatically appear when infants acquire new forms of balance and locomotion. Instead, flexibility is learned over many weeks of everyday locomotor experience in a newly acquired posture. Infants learn how to learn as they acquire the appropriate exploratory behaviors for generating information about the current constraints on action and potential alternatives for achieving their goals. Two kinds of limits on flexibility are described—one created by developmental transitions to new postural control systems and the other created by the nature of the perceptual information for friction and rigidity.

Keywords: flexibility, learning, motor action, infants, balance, locomotion

Behavioral flexibility is the essence of goal-directed action. Flexibility is the wherewithal to cope with variable and novel circumstances: selecting adaptive responses to novel instances of a problem, modifying ongoing behaviors in accordance with changes in local conditions, and finding new means to achieve a desired outcome (Adolph, 2005; Adolph & Berger, 2006). Motor actions are movements of the eyes, head, limbs, and body that are geared to getting information about or interacting with the world. Flexibility is essential for motor action because variability and novelty are endemic in everyday activities. Local conditions are continually changing. Constraints on movement are always in flux. For actions to be adaptive and functional, movements must be selected and modified to suit the demands of the current situation (Bernstein, 1996; E. J. Gibson & Pick, 2000). Motor actions must reflect the here and now while simultaneously anticipating the immediate future (von Hofsten, 2003, 2004). Motor decisions must match the actual possibilities for action.

Learning to Learn

Flexibility refers to the creative and improvisatory nature of action. Motor actions require a variety of means, not the same movements over and over. To take current conditions into account while guiding action toward the intended goal, each movement must be performed a little bit differently. Even highly practiced actions such as walking cannot be a series of rote repetitions with each step exactly like the last because the everyday environment is not like a big gymnasium with uniform, open ground. In real life, paths are cluttered and ground surfaces are infinitely variable. Walking cannot be choreographed or prescribed by a preexisting plan because the everyday environment is not like a fixed obstacle course with all the challenges known ahead of time. Instead, the precise nature of each challenge is always new. Walking speed and step length increase and decrease in preparation for navigating obstacles; legs rise to different heights to clear impediments or to lower the body; the torso twists or bends to slide through narrow passages or under barriers; arms swing freely, raise to the sides for balance, or grasp supports; double steps, back steps, cross steps, and side steps correct missteps; and new routes or alternative modes of locomotion are chosen if the path is impassable.

Flexibility, with its emphasis on discovery in the present moment, is akin to Harlow's (1949) notion of "learning to learn" (Adolph, 2002, 2005). As Stevenson (1972) put it, "The ultimate goal in any type of learning cannot be the retention of large amounts of specific information. For the most part, this information will be forgotten. What can be retained are techniques for acquiring new information, learning how to attend to relevant cues and ignore irrelevant cues, how to apply hypotheses and strategies and relinquish them when they are unsuccessful" (p. 307). In other words, rather than learning particular solutions for familiar problems, learners learn how to discover new solutions for new problems.

Perceptual information is the key to behavioral flexibility. Online exploratory behaviors generate the information needed to assess the current constraints on action and find an appropriate resolution. As J. J. Gibson (1979) pointed out, perceptual information provides the basis for adaptive motor decisions. Movements are embedded in a continuous cycle of perception and action in which what we are doing now provides feedback for deciding what to do next. Exploration and performance are fluid and interchangeable; every movement can serve both information gathering and performatory functions.

Optimally, perceptual feedback allows movements to be controlled prospectively ahead of time rather than reactively in response to an unexpected disruption (E. J. Gibson & Pick, 2000; Lee, 1993; von Hofsten, 1993). Reactive responses are often too late to prevent a mishap because the rate of neural conduction is relatively slow. Movements are prospective when modifications are anticipatory, that is, lifting a leg to clear the curb rather than attempting to recover balance after tripping on the obstacle. Prospective control requires anticipating a shift in the body's center of mass before lifting the arms rather than compensating after the fact for disrupted balance. Because movements are ongoing, prospective adjustments and reactive compensations often occur in concert (Adolph, Eppler, Marin, Weise, & Clearfield, 2000). A slight misjudgment in planning requires reactive adjustments; reactive adjustments, in turn, provide new information for planning the next step prospectively.

Chapter Overview

This chapter has two major aims. The first aim is to describe flexibility in motor action. We use balance and locomotion in infants as a test case for understanding three aspects of behavioral flexibility—adaptive motor decisions, modification of ongoing activity, and new means to achieve a goal.

Thus, we begin by describing why infant balance and locomotion make an apt model system for investigating flexibility in action. Next, we report evidence that infants do in fact exhibit behavioral flexibility and that adaptive motor decisions are related to infants' real-time exploratory behaviors that obtain the relevant perceptual information.

Our second aim is to illuminate the links between flexibility and development. In particular, we demonstrate that flexibility is acquired during development and that developmental changes both facilitate and impede its acquisition. In subsequent sections, we show that flexibility does not automatically appear when infants acquire new forms of balance and locomotion. Instead, flexibility is learned over many weeks of everyday locomotor experience in a newly acquired posture. Infants learn how to learn as they acquire the appropriate exploratory behaviors for generating information about the current constraints on action and potential alternatives for achieving their goals. Finally, we describe two kinds of limits on flexibility, one created by developmental transitions to new postural control systems and the other created by the nature of the perceptual information for friction and rigidity. We conclude with a final discussion of flexibility in development.

Infants in Balance

For adults, keeping balance is integrated into the body's movements so seamlessly and effortlessly that, like breathing, we do not appreciate its importance until something goes wrong. We do not appreciate its difficulty until we attempt to perform a new postural skill. A lower back muscle spasm is a rude reminder that posture underlies all bodily movements. Attempting to ski or roller blade for the first time is an embarrassing lesson that illustrates that the art of maintaining balance is acquired one step at a time. For infants, achieving a stable posture is a tremendous struggle. The developmental status of infants' postural control is the primary impediment and facilitator of their ability to explore and act on the world.

Balance Is Basic

A primary reason to focus on balance and locomotion for the study of flexibility is that these behaviors are fundamental for motor action. Balance is the foundation on which all movements of the head, limbs, and torso are built (Adolph & Berger, 2006; Reed, 1982). Stationary postures are not like frozen stone statues. The term "stationary" is really a misnomer because the body is continually in motion. Unless infants are lying flat on the ground, their bodies are always fighting the pull of gravity. Even sitting and standing postures that look stationary to casual observation are actually postures in motion. High-resolution motion recordings show that the body is gently swaying inside its base of support. Electromyographic recordings show that the muscles are actively engaged in balance control. As the body sways in one direction, a compensatory sway pulls it back in the opposite direction.

Moreover, when infants move their various body parts while sitting or standing, balance becomes more complicated. As the head turns or an arm lifts, the torso must tighten to stabilize the body. A forward lean necessitates compensatory torques by opposing body parts. Like the old song says, the toe bone is connected to the foot bone, and the foot, leg, knee, hip, back, neck, and head bones are connected all the way up. Failure to generate the appropriate compensatory sway or to stabilize the body against movements of the extremities can result in loss of balance, and the baby will fall down.

Balance is also integral to locomotor postures. During locomotion, balance is dynamic because the base of support is moving rather than stationary. To achieve dynamic balance, infants must deliberately induce disequilibrium to shift the body weight outside the current base of support and to produce the propulsive forces necessary to move the body. To prevent falling, the base of support moves to 'catch' the body. In crawling and walking, for example, the base of support shifts forward in anticipation of catching the body as the moving limb swings forward from step to step. Thus, locomotion is a series of controlled near falls.

A second reason to focus on balance and locomotion is that these activities are so common. A typical walking infant, for example, is on the floor engaged in balance and locomotion for 6 hours each day. Based on naturalistic observations of infants in an indoor play room, we estimate that the average 14-month-old toddler takes nearly 15,000 steps each day, traveling the distance of 45 football fields and incurring over 100 (fortunately, inconsequential) falls (Adolph, Badaly, Garciaguirre, & Sotsky, 2008). A typical crawling infant is on the floor for 5 hours per day, taking over 3,000 crawling steps, and covering the distance of two football fields (Adolph, 2002).

A third reason for focusing on balance and locomotion is the intense demand for flexibility in everyday activities. Every movement of the body—reaching for a cup of coffee, nodding the head, even drawing a deep breath—changes the location of the center of mass and the destabilizing torques acting on the body. Every variation in the ground surface (e.g., slant, elevation, traction, rigidity), in the body's functional dimensions (growth, clothing, loads), in physical ability (strength, reaction time, coordination), in task demands (running the 50-yard-dash versus running a marathon), in the goal (being fast versus being accurate, making a beeline to the destination), and in the available perceptual information (visual cues from a distance, overhead lighting conditions, the feel of the ground underfoot) affects the biomechanical and psychological constraints on balance and locomotion.

Developmental Constraints on Balance

We study flexibility in infants rather than adults because variability and novelty are dramatically heightened during the infancy period. The demand for flexibility is especially high. Over the first 2 years of life, infants' environments enlarge with a wealth of new surfaces and goals, their bodies undergo radical changes in size and proportions, and their motor skill levels rapidly improve. Most unique to the infancy period is the acquisition of new ways of stabilizing the body and of moving the body from place to place: Infants acquire new postural control systems in development.

For infants, environmental features can be truly novel. Frequently, infants who visit our laboratory in New York City have yet to walk over a sidewalk, play on grass, stand on sand, step onto ice, or encounter a flight of stairs. More generally, for most infants everywhere, sloping ground, deformable and slippery surfaces, loose traction, abrupt drop-offs, narrow apertures, overhead barriers, and underfoot obstacles may be novel.

Moreover, changes in infants' bodies and skills introduce them to new aspects of the environment. With the advent of independent locomotion, infants can go to see what is around the corner or in the next room. Crawlers' eyes are pointed toward the ground, and with their hands in front, tactile information inadvertently reveals the substantial properties of the ground surface. In upright postures, infants can peer over the top of the coffee table and see what is happening above their parents' knees. Their eyes are pointed farther ahead, and tactile exploration is performed primarily with the feet.

Infants' body growth is traditionally depicted as a continuous increase in size (height, weight, head circumference, and so on) with a corresponding decrease in overall chubbiness and top-heavy proportions (Kuczmarski, 2000). In actuality, growth is episodic. Infants' height, for example, stays the same for 2 to 28 consecutive days and then, in the course of a single day, suddenly increases by 0.5 to 1.65 centimeters (Lampl, Veldhuis, & Johnson, 1992). Episodic development is also characteristic of changes in infants' weight, head circumference, and leg bone growth. The long bones grow faster than the skull and muscle mass accumulates faster than fat so that infants become leaner and stronger as they grow longer, and their bodies become less light-bulb shaped and more cylindrical (Adolph & Berger, 2005). All the while, the center of mass lowers relative to the height of the body. Body growth, of course, changes the biomechanical constraints on balance and propulsion. The episodic nature of infants' body growth makes the demand for flexibility even greater.

Concurrent with changes in infants' bodies are rapid changes in their skill levels. When infants first begin crawling and walking, for example, their steps are small, shaky, and slow. New walkers splay their legs so far apart that their step widths are larger than their step lengths. Short periods with the limbs in the air are punctuated by long periods with the limbs on the floor. Step length and velocity increase exponentially over the first few months of crawling and walking, showing the negatively accelerated performance functions characteristic of improvements in motor skill acquisition (Adolph, Vereijken, & Denny, 1998; Adolph, Vereijken, & Shrout, 2003; Bril & Ledebt, 1998). As a consequence, a poorly skilled infant last week may become highly proficient next week, and a speedy, sturdy crawler will soon become a slow, unsteady walker. Infants must take these rapid changes in their abilities into account when making decisions about motor action.

Quantitative improvements in balance and locomotion are only part of the story. Changes are qualitative as well. At birth, when infants lie prone, their necks are so weak that they can barely pull their faces from the mattress to turn their heads from side to side. When held in a sitting position, their heads loll forward until their chests rest on their knees. When held upright, they cannot support any of their body weight.

Over the ensuing months, infants acquire the means to conquer gravity with a series of qualitatively different postural control systems: sitting, crawling, cruising, and walking (Figure 19.1). In a sitting posture, infants keep balance with their legs outstretched in a "V" shape or bent backward at the knees, beneath their bottoms, in a "W." Some locomote by "bum shuffling" using their arms to move their body forward or hitching using one leg to do the work of propulsion. In a crawling posture, infants keep balance only momentarily while using their bellies for support, or they keep balance on hands and knees or hands and feet with their abdomens suspended in the air. In a cruising posture, infants move upright, in a sideways position, holding onto furniture for support. Their arms do most of the work of balance and propulsion and support some of their body's weight. In a walking posture, infants face forward with their arms free, and they support all of their body weight on one leg while the other swings forward. The postures are qualitatively different because they involve different body parts for balance and propulsion, muscle actions to perform the movements, key pivots about which the body rotates, regions within which the body can sway without falling, vantage points for viewing the ground ahead, sources of perceptual information for controlling balance and locomotion, and so on.

On average, infants achieve sitting at around 6 months of age, crawling on hands

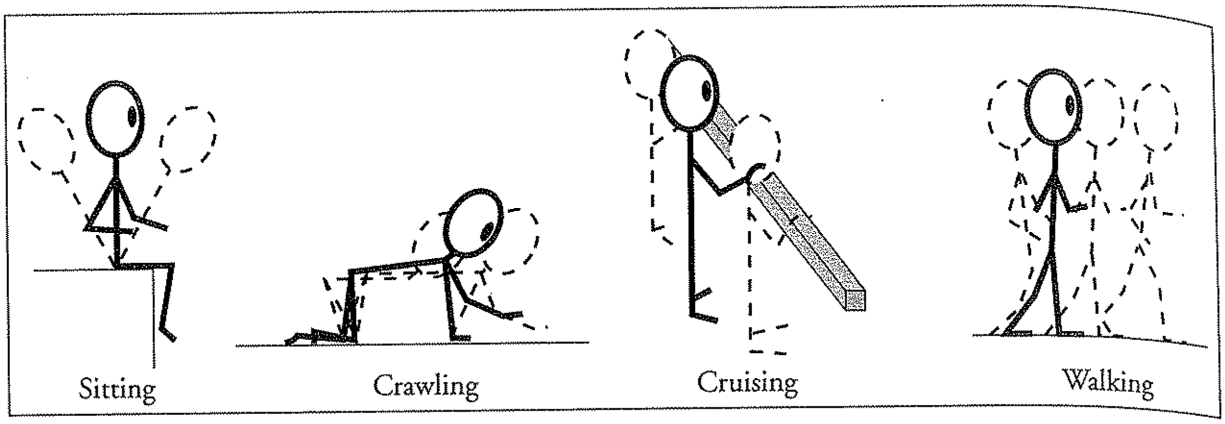


Fig. 19.1 Four postural control systems—sitting, crawling, cruising, and walking—depicted in their typical order of emergence in development. Each posture requires different strategies for maintaining balance, obtaining relevant perceptual information, and moving the body from place to place during locomotion. The dashed lines represent the body's swaying motions during static and dynamic balance. Adapted with permission from Adolph, K. E., & Eppler, M. A. (1998). Development of visually guided locomotion. *Ecological Psychology, 10,* 303–321. Lawrence Erlbaum Associates.

and knees at 8 months, cruising sideways along furniture at 9 months, and walking at 12 months (Capute, Shapiro, Palmer, Ross, & Wachtel, 1985; Frankenburg, Fandal, Sciarillo, & Burgess, 1981). However, the ages and order of acquisition vary wildly between infants. For example, some babies walk at 7 months and others at 17 months; some infants crawl before sitting or after walking, and some infants never crawl at all. The most important point is that qualitatively different forms of postural control appear staggered over many months of development so that at the same point in time, infants are experts in an earlier developing posture and novices in a later developing one.

Flexibility in Infant Action

Given the tremendous variability and novelty in infants' environments, bodies, and skills, flexible responding is an impressive feat. Here, we describe three examples of flexibility in infants' balance and locomotion. In the first example, infants faced novel variations in the surface layout: They were challenged to walk over a walkway with variable slant. In the second example, they adapted to novel variations in their bodies and skills: They walked while carrying heavy loads. In the third example, they used a tool as a means for achieving their goals: They crossed bridges of variable widths with and without a handrail available to augment their balance, and in some cases the material properties of the handrail varied.

In each task, infants demonstrated flexibility in several ways. Most important, their responses were adaptive: Their decisions about whether to walk matched the actual possibilities for walking. Moreover, they modified their ongoing exploratory activity and walking patterns in accordance with the constraints imposed by the novel manipulations, and they devised new means for dealing with the novel challenges.

Walking Over Slopes

At 14 months of age, most infants have several weeks of walking experience, but few have encountered a steep slope on their own. Although young toddlers have ample opportunity to climb up onto furniture and other elevated surfaces, few have mastered descent of furniture, stairs or drop-offs. Thus, slopes are novel, especially for descent. To assess infants' ability to cope with the challenge of going up and down slopes, 14-month-old walking infants were observed on a large, mechanized walkway (Adolph, 1995). As shown in Figure 19.2, two flat platforms flanked a middle sloping platform. Slant could be adjusted in 2-degree increments from 0 to 36 degrees by pumping a car jack that raised and lowered the bottom platform. Caregivers stood at the far side of the walkway and encouraged infants to come up or down, using toys and dry cereal as incentives. An experimenter followed alongside infants to ensure their safety if they began to fall.

Each infant was observed on the full range of slopes over dozens of trials. Because infants' body dimensions and walking skill vary widely at the same chronological age, the identical degree of slant could be perfectly safe for one infant but impossibly risky for another. Thus, risk level was determined on an individual basis using a psychophysical procedure to identify the steepest slope that each infant could walk up and walk down on at least 67% of trials—their "motor thresholds." Then infants were tested at various slopes incurring the same relative degree of risk across participants. Slopes shallower than the threshold increment were increasingly safe, meaning that the probability of walking successfully increased. Slopes steeper than the threshold increment were increasingly risky, meaning that attempts to walk were likely to result in falling.

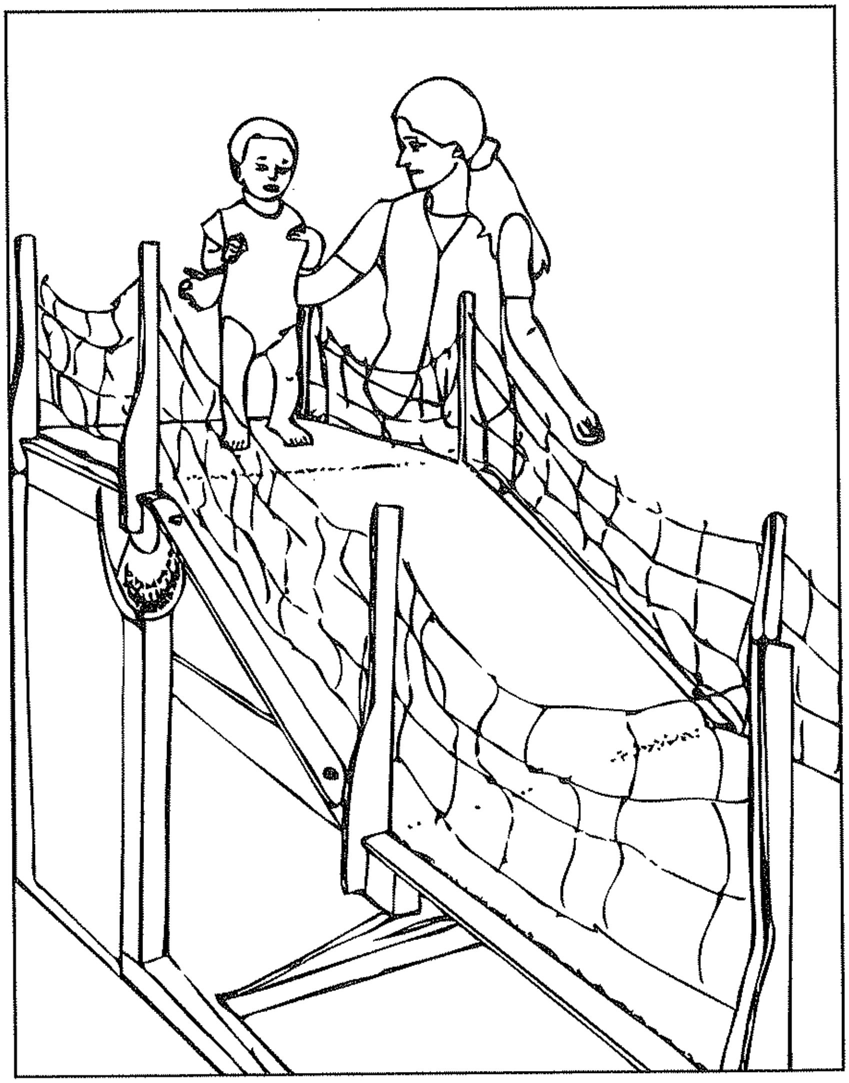


Fig. 19.2 Adjustable sloping walkway. Infants began at one end of the walkway, and caregivers (not shown) stood at the far end of the walkway offering encouragement. An experimenter (shown) walked alongside infants to ensure their safety. In addition, safety nets lined the sides of the walkway, and a plush carpet provided cushioning against falls. Adapted with permission from Adolph, K. E., & Avolio, A. M. (2000). Walking infants adapt locomotion to changing body dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1148–1166. American Psychological Association.

Motor thresholds showed large individual differences (8 to 24 degrees for uphill and 6 to 28 degrees for downhill), confirming the need for the normalization procedure. The primary question regarding flexibility was whether infants' motor decisions were adapted to their own level of walking skill and to the variations in the degree of slant from trial to trial. Would infants detect the different possibilities for walking over safe and risky slopes and adjust their behavior accordingly?

As shown in Figure 19.3A, infants' motor decisions were scaled to their own abilities. Infants attempted to walk up and down safe slopes on nearly every trial and refused to walk over increasingly risky slopes. For ascent, the average attempt rate decreased from 0.99 at the threshold increment to 0.23 on slopes ≥18 degrees steeper than the threshold increment. For descent, the attempt rate decreased from 0.94 to 0.11. The difference in attempt rates between uphill and downhill trials reflected the different consequences of falling in each condition. While walking uphill, infants' hands are in front of their bodies, and they can safely catch themselves if they fall. Walking downhill is more treacherous because infants' hands are poorly positioned to break a fall, the distance to fall is farther, and infants' bodies are moving faster as they build up forward momentum. In line with these different consequences, on uphill trials, infants appeared unruffled when they fell, but on downhill trials, they fussed as if the sensation of falling downward were aversive.

Infants also displayed flexibility by modifying their walking patterns in accordance with the degree of slant and the different demands of going uphill or down (Figures 19.3B and 19.3C). On safe slopes shallower than the threshold increment, they walked straight up or down after only a brief glance at the obstacle. Similarly, on risky uphill slopes, latency and touching increased only slightly. But on risky downhill slopes, latency and touching increased sharply. Latency provided a crude measure of visual exploration because infants looked toward the landing platform nearly all of the time that they hesitated at the brink. Touching provided a measure of tactile exploration. Touches were typically brief (only a few seconds) but occurred on 23% of risky slopes. As they slowed down and stopped at the edge of the slope peering downward, infants touched the surface with a foot. They stood at the brink of the slope and rocked back and forth around their ankles, they took tiny steps with their feet straddling the brink, and they poked out one foot to pat or rub the sloping surface while grasping a support post with their hands to keep balance.

Additional evidence for flexibility was infants' variety of means for coping with slopes. Risky slopes required avoidance or an alternative means of descent. On risky uphill trials, infants never avoided ascent. Instead, they quickly shifted from their upright posture to all fours and clambered up the slope on hands and feet (dashed curve in Figure 19.3D). As they felt their bodies slide, they turned their toes under to get a better grip. On risky downhill trials, infants explored alternative means of descent by testing what different positions felt like before committing themselves to traversal (solid curve in Figure 19.3D). They executed multiple shifts in position (≥2 shifts) on 43% of the 225 risky downhill trials, and the number of shifts ranged up to 10. For example, in a typical long sequence, one infant shifted from standing upright to a backing position with his legs dangling down the slope, perched on hands and knees, sat down facing the bottom platform, stood back up, returned to a backing position, and finally spun around to a sitting position and slid down.

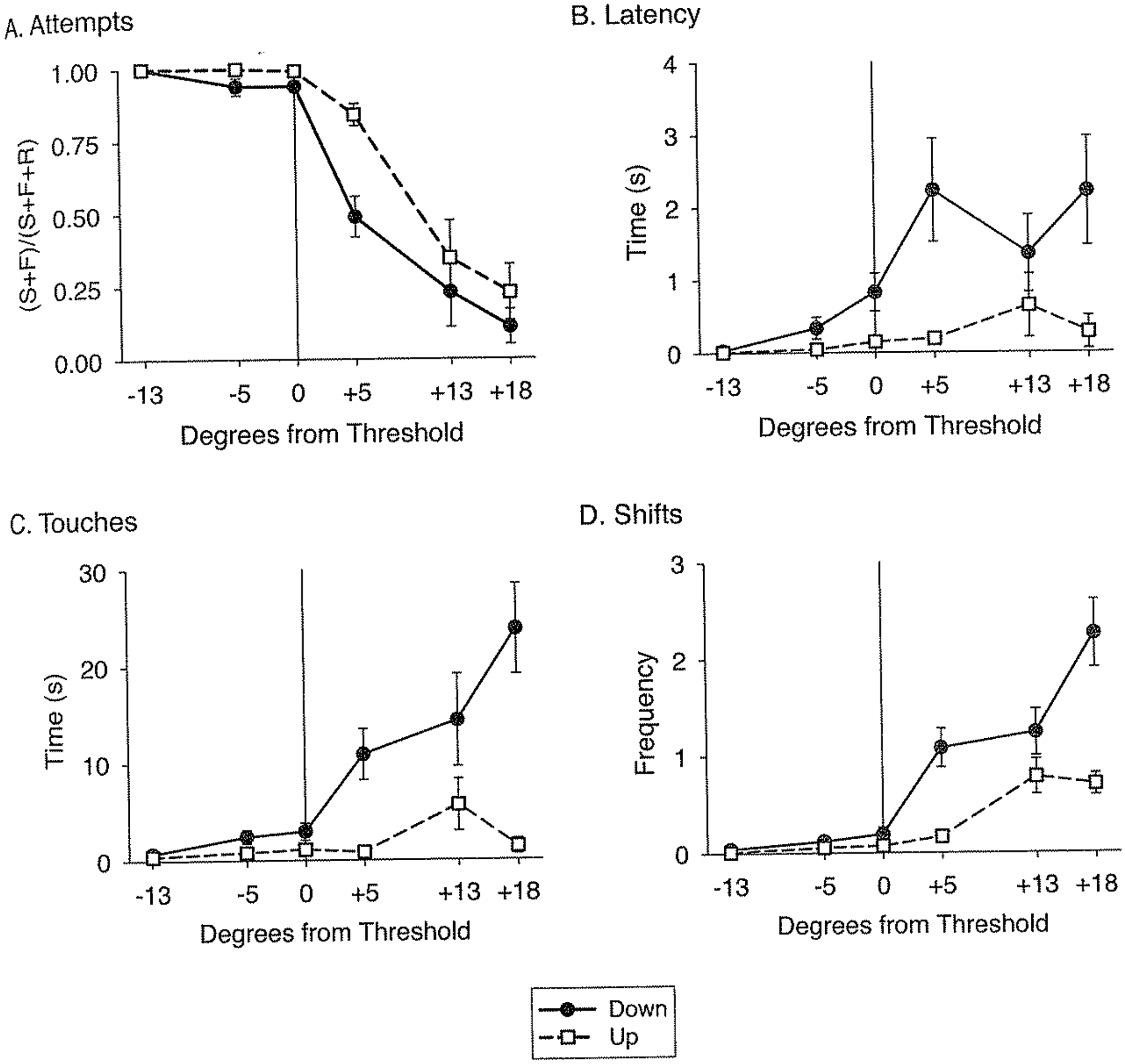


Fig. 19.3 Fourteen-month-old infants' motor decisions and exploratory behaviors on uphill (dashed curves) and downhill slopes (solid curves). Mean values of (A) attempts to walk, (B) latency, (C) accumulated duration of touching, and (D) number of position shifts. Data are shown normalized to each infant's motor threshold (denoted by solid, vertical lines at 0). On the x-axis, negative numbers to the left of the threshold represent safe slopes, and positive numbers to the right of the threshold represent risky slopes. Error bars indicate mean standard errors. Reproduced with permission from Adolph, K. E. (1995). Psychophysical assessment of toddlers' ability to cope with slopes. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 734–750. American Psychological Association.

Exploratory shifts in position paid off because infants discovered varied means for descending risky slopes. They avoided descent on only 18% of downhill trials. For the remaining 82% of trials, they discovered alternative methods of locomotion (Figure 19.4). They crawled down, slid headfirst prone with their arms outstretched like Superman, slid down in a sitting position, and backed down feet first with their faces turned away from the bottom platform. Although sitting and backing were the most common descent methods, most infants used multiple means, averaging 2.23 different methods for descending risky slopes (Siegler, Adolph, & Lemaire, 1996). On trials in which infants shifted multiple times, they nearly always refused to walk and nearly always selected an appropriate alternative, providing further evidence that their shifts on the starting platform reflected a search for alternative means.

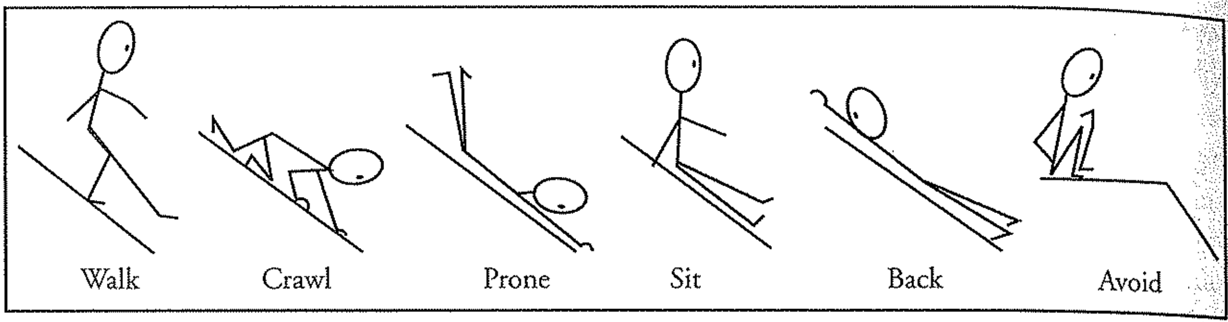


Fig. 19.4 Strategies for descending slopes: walking, crawling on hands and knees, sliding head first prone, sitting, backing feet first, and avoiding descent. Adapted with permission from Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251). Wiley-Blackwell Publishing Ltd.

Walking With Loads

The second example provides an even more impressive demonstration of flexibility: Fourteen-month-old walking infants adapted to experimental manipulation of their body dimensions while simultaneously gauging possibilities for walking down slopes (Adolph & Avolio, 2000). Infants were tested on an adjustable sloping walkway, but this time slant varied from 0 to 90 degrees in 4-degree increments via a push-button remote that operated an electric motor. In addition, infants wore a fitted vest with removable shoulder packs that altered their body dimensions (Figure 19.5). On some trials, the shoulder packs were filled with lead weights distributed symmetrically around their chests and backs (25% of each infant's body weight; $M = 2.59$ kg); on other trials, the packs were filled with feather weight, Polyfil stuffing. The lead-loaded packs increased infants' overall mass and raised their center of mass, making their bodies more top heavy and their balance more precarious, especially while walking down slopes. The featherweight packs increased the circumference of infants' torsos by the same amount as the lead-weight packs but did not affect infants' ability to keep balance. As in the previous study, a psychophysical procedure was used to normalize the degree of risk to each infant's ability in each of the load conditions. But now, two psychophysical protocols were interleaved so that infants had to discover at the start of each trial whether

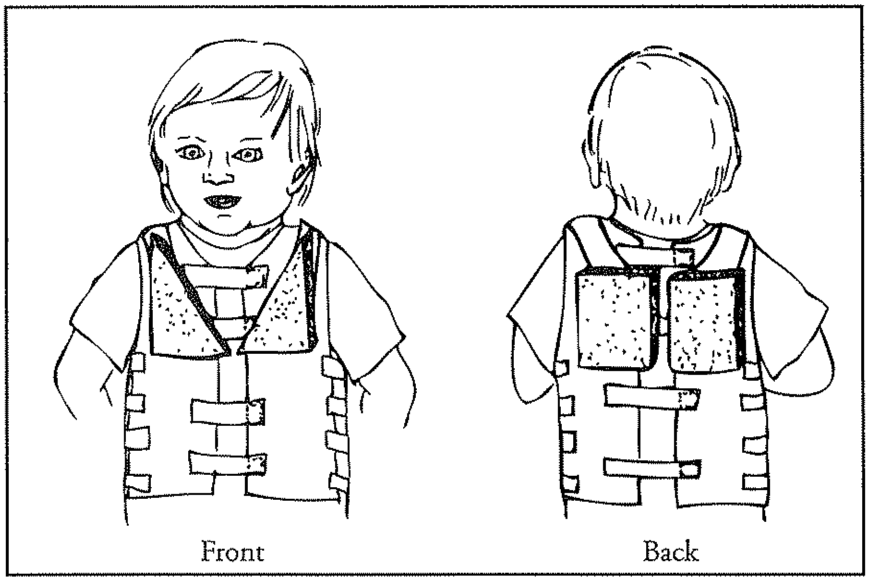


Fig. 19.5 Front and back views of adjustable vest loaded with lead weight or feather weight shoulder packs. Velcro tabs allowed quick fastening and removal of packs on infants' chests and backs. Reproduced with permission from Garciaguirre, J. S., Adolph, K. E., & Shrout, P. E. (2007). Baby carriage: Infants walking with loads. *Child Development, 78,* 664–680. Wiley-Blackwell Publishing Ltd.

the shoulder packs were loaded with the lead weights or the feather weights—that is, whether their walking skill was altered.

The lead-weight packs impaired infants' ability to walk down slopes, indicating that more top-heavy body dimensions had a detrimental effect on walking skill. Infants executed more modifications in their walking patterns (e.g., took shorter, slower steps) while descending slopes wearing feather-weight packs compared with lead-weight packs. Without the ability to modify step length and velocity with lead weights, gravity and momentum took over, pulling infants down the slope. As a consequence, infants' motor thresholds decreased while walking down slopes wearing the lead-weight packs, (*M* threshold for feather weights = 12.00 degrees; *M* threshold for lead weights = 7.60 degrees).

As in the previous study, infants scaled their motor decisions to the relative degree of risk. In both conditions, attempts to walk were high, near 1.0, on safe slopes, and decreased sharply over risky slopes to 0.32 at slopes 18 degrees steeper than the threshold increment and to 0.20 at slopes 40 degrees steeper than the threshold. In the current study, infants also showed flexible adaptation to their altered bodies and skills. They detected the added body mass induced by the lead weights and anticipated how the load would affect their walking abilities when deciding whether to walk down slopes. The same absolute degrees of slant between their feather- and lead-weight thresholds were safe while they were wearing their feather-weight packs and risky while wearing their lead-weight packs. Accordingly, infants correctly showed higher attempt rates on the same absolute degrees of slant in the feather-weight condition than in the lead-weight condition.

Infants also modified their exploratory movements in line with the degree of slant and the load condition. Latency increased with relative risk in both load conditions, meaning that infants slowed down while approaching risky slopes and hesitated longer before stepping over the brink. However, infants had to keep their bodies stiffly upright to prevent themselves from being pulled over by the lead weight packs, and this interfered with their ability to execute exploratory postural sway at the edge of the starting platform and to rock back and forth over their ankles at the brink. Thus, exploratory touching was slightly depressed in the lead-weight condition. The lead weights, however, did not interfere with infants' use of alternative means for descent. In both load conditions, they avoided descent on less than 20% of trials in which they refused to walk. They descended risky slopes by sliding down in various positions: primarily sitting and backing feet first but also crawling, headfirst prone, and clinging onto the safety nets for support while standing upright.

To determine the extent of infants' ability to modify their walking patterns in response to loads, another group of 14-month-olds were observed while carrying loads over flat ground (Garciaguirre, Adolph, & Shrout, 2007). Infants wore the same vest used in the previous study. This time, the lead weights were lighter (15% of infants' body weight), and the load was distributed symmetrically (divided evenly on the front, back, and sides of the vest as in the previous study) and asymmetrically over infants' bodies (all load carried on infants' front, back, left side, or right side). Although infants carry loads in their arms nearly as soon as they can walk, few infants carry loads on their backs in baby backpacks or over one shoulder in a baby purse or satchel, and loads are not placed on the shoulders above infants' center of mass. Thus, the manipulation of infants' body dimensions was relatively novel.

A mechanized carpet covering the flat testing surface recorded modifications in infants' footfall patterns (step length, velocity, and the period of time that their feet were on the ground and in the air). Video recordings revealed modifications in infants' posture (leaning forward, backward, and to the right and left sides) and disruptions in their walking patterns (tripping, falling, double steps with the same foot, zigzagging cross steps, and back steps).

Here, evidence for flexibility was primarily reactive because the load distribution varied from trial to trial, requiring infants to respond as they felt their bodies pulled in one direction or another as they began to walk. As in the previous study, infants kept their bodies stiffly upright in the symmetrical condition. However, in the asymmetrical conditions, infants modified their body posture by leaning. To our surprise, infants leaned with the load rather than in the opposite direction (e.g., they leaned forward like ski jumpers while carrying the front load and backward like walking into a wind tunnel while carrying the back load). In contrast, older children and adults compensate for asymmetrical loads by leaning in the direction opposite to the load (e.g., leaning forward while wearing a heavy backpack and leaning to the right while carrying a suitcase in the left hand). The adults' strategy keeps the center of mass inside the base of support. The infants' strategy allows the loads to pull the center of mass outside the base of support.

Infants' gait modifications were in response to their altered body posture. To offset the shift in their center of mass induced by leaning with the loads, they modified their footfall patterns so as to maintain dynamic balance. They shortened their step length, decreased their step velocity, planted their moving foot on the floor as quickly as possible, and increased the period of time when both feet were on the floor. In the side-load condition, infants limped, spending less time swinging their leg through the air on the side carrying the load. The back-load condition—the most novel—was most difficult, causing the highest number of gait disruptions and the greatest magnitude of gait modifications. Infants with more walking experience showed fewer gait disruptions and subtler gait modifications, indicating that they were more adept at keeping balance.

Crossing Bridges

In the third example of flexibility, infants were challenged with novel variations in the surface layout, but also provided with the opportunity to incorporate a tool into their

A) No Handrail

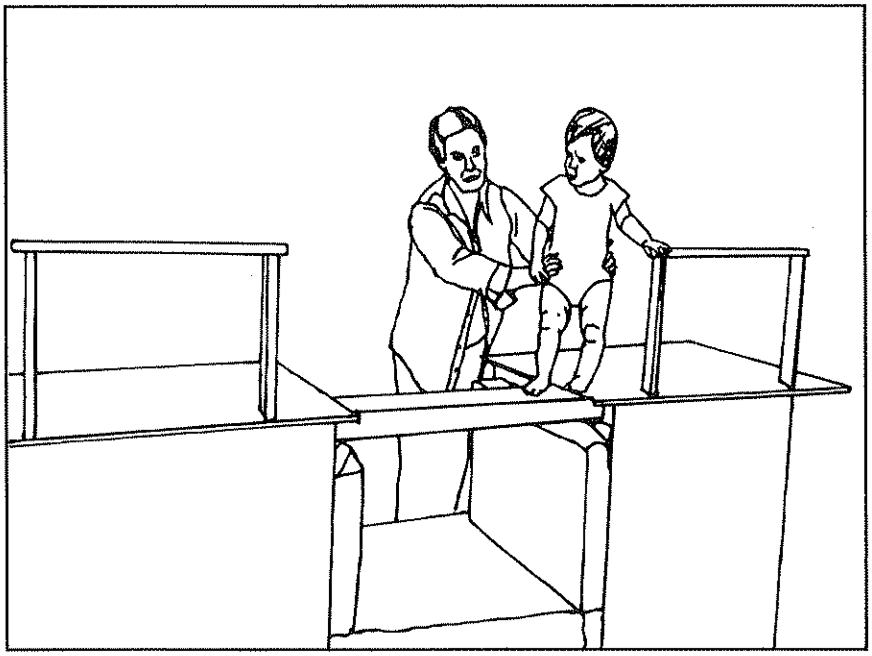
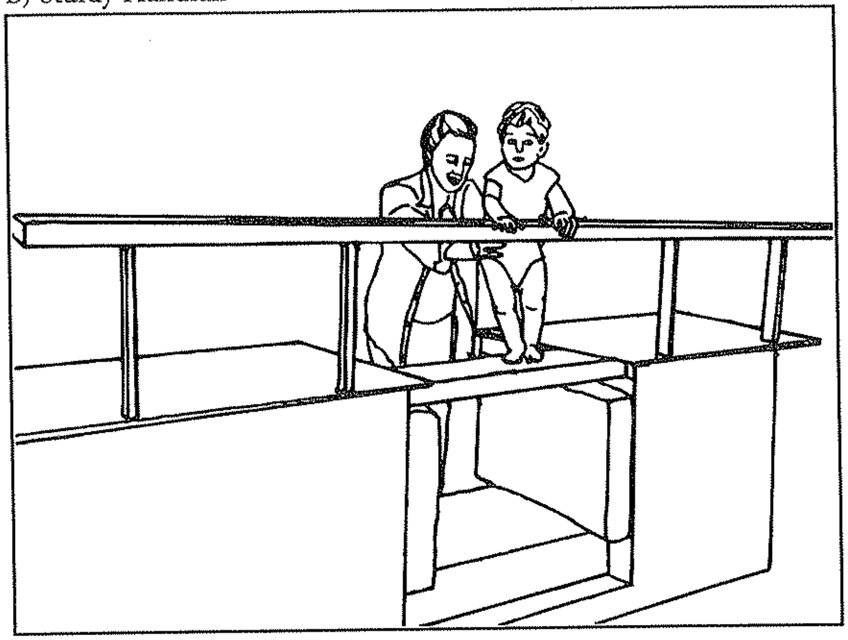


Fig. 19.6 Adjustable bridge apparatus. Two platforms were connected by bridges varying in width. A removable handrail could be placed on permanent support posts. Depending on the condition, infants were encouraged to cross bridges (A) without a handrail to augment their balance;

B) Sturdy Handrail



C) Wobbly Handrail

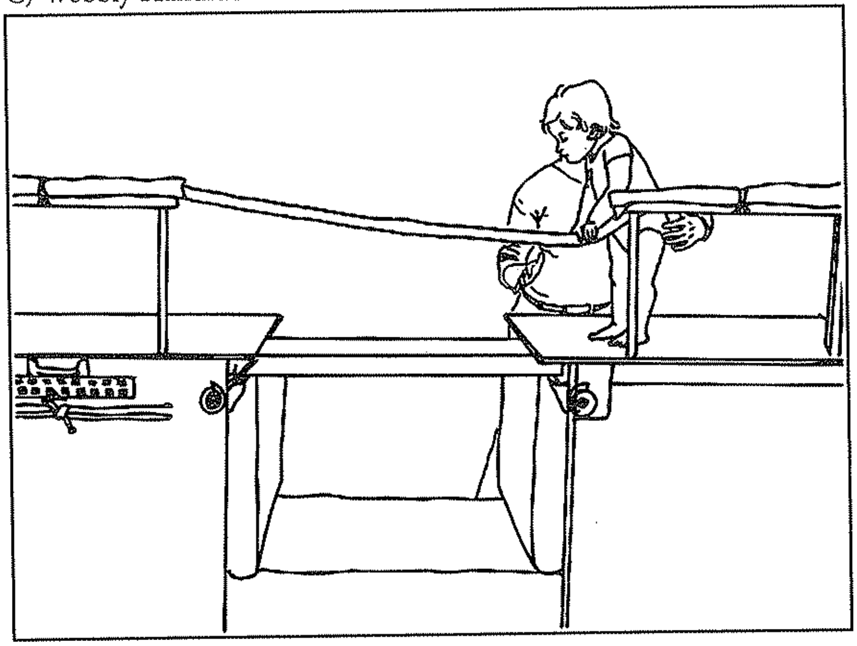


Fig. 19.6 (*continued*) (B) with a sturdy, wooden handrail; or (C) with a wobbly handrail that deformed beneath their weight. Caregivers (not shown) encouraged infants to cross from the far side of the finishing platform. An experimenter (shown) walked alongside infants to ensure their safety. As an additional precaution, the area under the bridge was lined with foam cushions. Figures 19.6A and 19.6B reproduced with permission from Berger, S. E., & Adolph, K. E. (2003). Infants use handrails as tools in a locomotor task. *Developmental Psychology, 39,* 594–605. American Psychological Association. Figure 19.6C reproduced with permission from Berger, S. E., Adolph, K. E., & Lobo, S. A. (2005). Out of the toolbox: Toddlers differentiate wobbly and wooden handrails. *Child Development, 76,* 1294–1307. Wiley-Blackwell Publishing Ltd.

motor plan. As shown in Figure 19.6, 16-month-old walking infants were encouraged to cross bridges of variable widths (12–72 cm) spanning a deep, foam-filled precipice (Berger & Adolph, 2003). On half the trials, a solid wooden handrail spanned the walkway, and on half the trials, the handrail was removed. Caregivers coaxed infants to cross from the far side of the precipice, using toys and snacks as incentives, while an experimenter followed alongside infants to ensure their safety. The adults did not point out the handrail or encourage infants to use it.

Infants' motor decisions depended on both bridge width and handrail presence, indicating that they detected the changing possibilities for walking and the utility of the handrail for augmenting their balance. They fell on only 6% of trials, indicating that their responses were highly adaptive. Infants ran straight across the wider bridges regardless of whether the handrail was present, and they rarely touched the handrail as they whizzed past. For example, infants walked over the 72-centimeter-wide bridge on 100% of trials regardless of handrail presence and used the handrail for crossing on only 7% of trials. However, on the narrowest bridges, attempt rates were low in both handrail conditions, and when infants crossed, they clung onto the handrail with both arms. On the 24-centimeter bridge, they walked on only 48% of trials when the handrail was absent. In contrast, infants walked on 90% of trials when the handrail was available and used it to cross on nearly every trial. On the 12-centimeter bridge, they walked on only 14% of trials when the handrail was absent. They walked on 39% of trials when it was available and used the handrail on 93% of those trials.

Infants modified their ongoing activity before stepping onto the bridge. Latency, touching the bridge and handrail, and exploratory shifts in position increased as bridge width decreased. Infants explored the bridge by rubbing it with their hands or feet. They explored the handrail by gripping and patting it. Sometimes, they explored the handrail and the bridge simultaneously by holding onto the handrail and rubbing one foot over the edge of the bridge. Infants shifted from upright to squatting, crawling, sitting, and backing positions, suggesting that they were searching for alternative means to cross. Exploratory looking, touching, and position shifts were associated with higher rates of successful crossing.

Infants also modified their walking patterns after stepping onto the bridge. They crossed the widest bridges in an average of 1.30 seconds with only a handful of large steps ($M = 5.25$). In contrast, they crossed the narrowest bridges in 31.23 seconds and 21.56 tiny steps. While crossing upright, infants implemented varied strategies, sometimes facing frontward, sometimes turning sideways to face the handrail, and sometimes turning their back to the handrail and holding onto it with their hands behind their back.

A follow-up study showed that infants also take the material properties of the handrail into account when assessing its use a tool to augment their balance (Berger, Adolph, & Lobo, 2005). Another group of 16-month-olds were tested on the same apparatus with 10- to 40-centimeter bridges. This time, a handrail was available on all trials, but the material property of the handrail varied from trial to trial. On some trials, the handrail was made of sturdy wood and could easily support infants' full body weight. On other trials, the handrails were made of flexible foam or latex, and they drooped below infants' knees when they leaned their full weight on them.

As in the previous study, infants' motor decisions were highly adaptive: They fell on only 7% of trials. On wide bridges, infants ignored the handrail and ran straight across. On narrower bridges, attempts to walk decreased and handrail use increased. Infants hesitated longer before stepping onto the bridges, and exploratory touches of the bridge and handrail increased, especially on trials with the wobbly handrails. Exploratory touching was tailored to the material composition of the handrails. Infants tapped the wooden handrail more than the wobbly ones and squeezed, pushed, or rubbed the wobbly handrails more than the wooden one. They also explored the wobbly handrails by mouthing them.

To our surprise, infants preferred a wobbly handrail to no rail at all even though the wobbly handrails were flimsy and could not support their full weight. They crossed narrow bridges more often with the wobbly handrail than infants facing the same bridge widths with no handrail in the previous study, and their attempts were largely successful. How did infants manage to outwit three seasoned experimenters' best-laid plans? Infants devised clever, new solutions for crossing the narrow bridges by exploit-

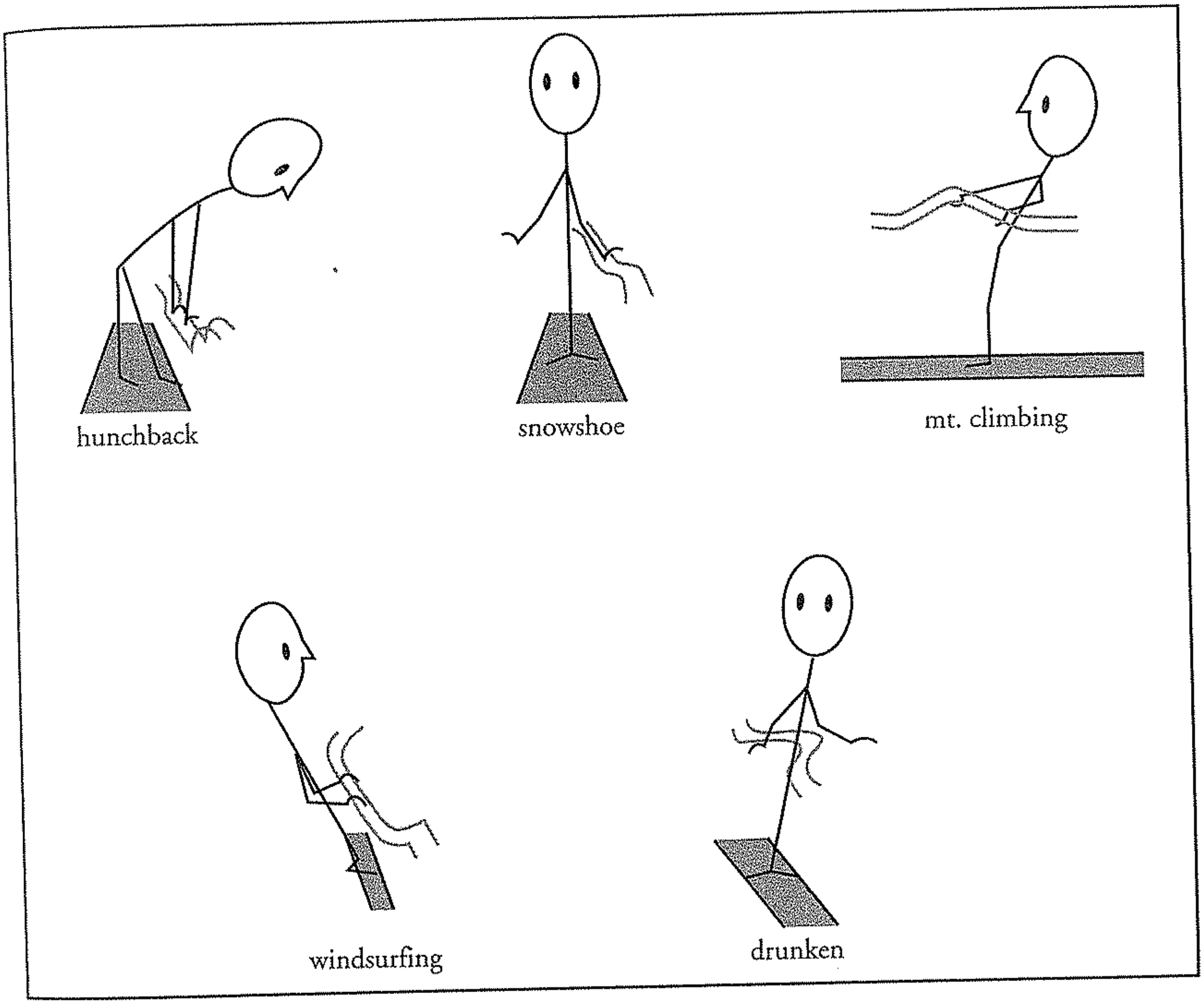


Fig. 19.7 Alternative strategies for crossing bridges with wobbly handrails. Hunchback: facing the handrail, walking sideways, stooped over, pressing down on the handrail. Snowshoe: facing forward, distributing body weight over the entire arm while gliding it over the handrail. Mountain climbing: facing forward, leaning backward, pulling up on the handrail like a rope. Windsurfing: facing the handrail, walking sideways, leaning backward and pulling up on the handrail with both hands. Drunken: facing forward, leaning against the handrail as their torsos slid along it. Reproduced with permission from Berger, S. E., Adolph, K. E., & Lobo, S. A. (2005). Out of the toolbox: Toddlers differentiate wobbly and wooden handrails. *Child Development, 76,* 1294–1307. Wiley-Blackwell Publishing Ltd.

ing the wobbly, deformable properties of the handrails (Figure 19.7). For example, 10 infants used a "hunchback" strategy in which they walked sideways (facing the handrail), stooped over like a hunchback, and pressing down on the handrail. Six children used a "mountain-climbing" strategy in which they faced forward (toward the goal), leaned back, and used the handrail like a rope to pull themselves hand over hand across the bridge. Three children used a "windsurfing" strategy in which they faced the handrail and leaned far back while pulling up on the handrail with both hands.

Acquiring Flexibility

In the previous section, we showed that infants demonstrate flexibility in response to novel variations in the surface layout and to changes in their body dimensions and skill levels. We reported evidence that infants' motor decisions were geared to the actual possibilities for action. Infants modified ongoing exploratory and locomotor behaviors both prospectively and reactively. They gathered perceptual information to support their motor decisions and they adapted their walking patterns to the current conditions. And infants devised new means to cope with the novel challenges.

In this section, we provide evidence that flexibility is learned. When infants first begin sitting, crawling, cruising, and walking, they do not behave like the expert toddlers who dealt with slopes, loads, and bridges so competently. Their new skills, of course, are clumsy and disfluent, but novice infants do not appear to recognize the limits of their abilities. Their motor decisions are not matched to the actual possibilities for action, they do not modify their ongoing behaviors in accordance with changing constraints on balance and locomotion, and they do not search for alternative means to achieve their goal. The acquisition of flexibility requires a long, protracted period of everyday experience with balance and locomotion for infants to learn to recognize potential threats to balance, gather the relevant perceptual information, and use the information to respond adaptively—that is, for them to learn how to learn.

We illustrate the role of experience in flexibility with a longitudinal study of infants crawling and walking down slopes (Adolph, 1997). Outside the laboratory, parents agreed to keep their infants off playground slides and sloping ground surfaces for the duration of the study so that the slope task would be novel. Inside the lab, infants were observed on an adjustable sloping walkway (slant varied from 0 to 36 degrees in 2-degree increments). As in the previous slope studies, a psychophysical procedure was used to normalize risk level to each infant's ability at each test session. Infants were tested once every 3 weeks, from their first week of crawling until 13 weeks or so after they began walking. Most infants participated for more than 10 months. In addition, infants in a control group were tested at three matched session times (in their first and 10th weeks of crawling and in their first week of walking) to ensure that the results from the test group were not due to repeated practice effects on slopes. Both groups of infants showed three types of improvements over weeks of crawling and walking experience: Their motor thresholds improved as they learned to modify ongoing crawling and walking patterns, their motor decisions became more accurate and adaptive as they learned to detect the current constraints on action, and they discovered alternative means for descending slopes.

Gait Modifications

Everyday locomotor experience was related to improvements in infants' ability to crawl and walk over flat ground and in their ability to crawl and walk down slopes (Adolph, 1997). On flat ground, infants' crawling and walking movements became larger, faster, straighter, and less variable as their bodies became stronger and more coordinated. On slopes, infants' average motor threshold increased from 17.43 degrees in their first week of crawling to 24.79 degrees in their 10th week of crawling and from 5.47 degrees in their first week of walking to 14.97 degrees in their 10th week of walking.

Part of the improvement in motor thresholds over weeks of crawling and walking resulted from infants' increasing ability to modify their steps during descent. Infants curbed forward momentum by decreasing their step length and velocity and by braking between steps. They minimized destabilizing torques by keeping their bodies vertical to ensure that their center of mass remained inside their base of support. After weeks of crawling experience, for example, infants crawled down steep slopes with their arms stiffly extended, slowly moving their hands an inch at a time, their legs nearly immobilized, flexed tightly beneath their torsos. Similarly, after weeks of walking experience, infants used a braking strategy to inch their way down steep slopes (see also Adolph, Gill, Lucero, & Fadl, 1996; Gill-Alvarez &

Adolph, 2005). Infants implemented these gait modifications before stepping over the brink, indicating that flexible adaptation of ongoing locomotor patterns was controlled prospectively based on perceptual information about the relative difficulty of descent.

The increase in the group averages over weeks of crawling, however, masks important individual differences. In their first week of crawling, about half the infants crawled on their bellies with their stomachs dragging along the floor, and half crawled on their hands and knees, with their stomachs in the air. The belly crawlers were at an advantage for descending slopes because they could slither down headfirst without having to support their body weight on their arms. As a consequence, belly crawlers began with steeper thresholds than the hands-and-knees crawlers. For infants in both crawling groups, thresholds increased over test sessions. However, when the belly crawlers finally switched to crawling on their hands and knees, their thresholds decreased temporarily, reflecting the more difficult task of crawling headfirst down slopes while supporting their raised bodies on their arms, before increasing again as they gained experience with hand-and-knees crawling. For all infants, the switch from crawling to walking caused a significant decrement in their motor thresholds, reflecting the switch to a new postural control system and the more stringent demands of descending upright.

Across sessions, better crawling and walking on flat ground predicted steeper thresholds on slopes, indicating that general locomotor proficiency transferred to the novel slope context. Further evidence that general everyday experience leads to flexibility comes from the infants in the control group, who were tested only three times. Compared with the infants in the experimental group who received hundreds of trials on slopes over more than a dozen sessions, slopes were relatively novel for infants in the control group. Nonetheless, infants in the control group showed similar improvements in their motor thresholds from their first to tenth weeks of crawling (*M*s = 15.83 and 20.31 degrees, respectively) and a similar decrement in thresholds in their first week of walking (*M* = 5.50 degrees). Even gait modifications that seem specific to descending slopes—braking forward momentum, keeping the body vertical rather than perpendicular to the slope, and so on—do not require practice locomoting over slopes. Rather, everyday experience is sufficient to facilitate flexible adaptation of ongoing movements in novel contexts (Adolph et al., 1996; Gill-Alvarez & Adolph, 2005).

Motor Decisions

Everyday locomotor experience also facilitated improvements in infants' motor decisions (Adolph, 1997). As in previous studies, infants always attempted to crawl and walk down safe slopes shallower than their threshold, where the probability of success was high (dashed curve in Figure 19.8). However, on risky slopes steeper than the threshold increment, infants' motor decisions became more adaptive with each week of locomotor experience (solid curve in Figure 19.8). In their first week of crawling, infants attempted impossibly risky slopes on repeated trials, necessitating rescue by the experimenter; the average attempt rate was 0.68. Although they could clearly see and feel the slant, novice crawlers plunged over the brink as if they did not recognize that the risky increments were beyond their ability. Over weeks of crawling, errors gradually decreased. By their 10th week of crawling, attempt rates averaged 0.56. By 20 weeks of crawling, infants were experts, and their attempt rates were 0.11. Their exploratory movements were fast and efficient, and most infants could discern within a few degrees of slant whether slopes were safe or risky for their

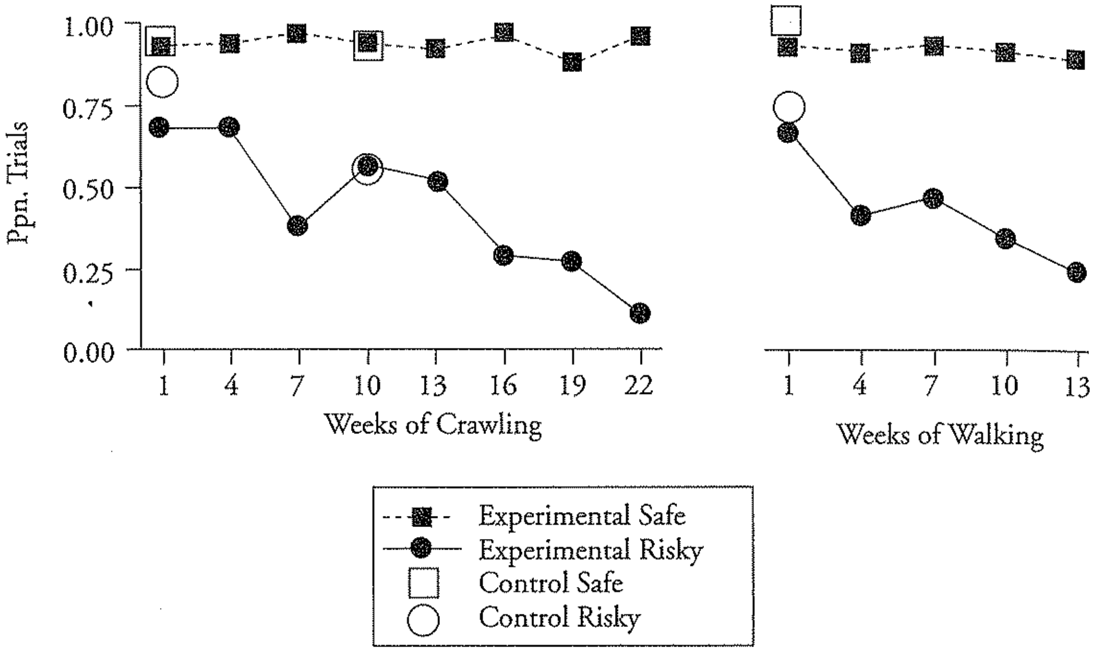


Fig. 19.8 Attempts to crawl and walk down slopes. Data were averaged over safe slopes (slopes ≤ the threshold increment, denoted by dashed lines) and risky slopes (slopes > the threshold increment, denoted by solid lines). Filled symbols represent data from the infants in the experimental group who were observed every 3 weeks, and open symbols represent data from the three sessions with infants in the control group. Reproduced with permission from Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251). Wiley-Blackwell Publishing Ltd.

current level of crawling skill. Similarly, in infants' first week of walking, errors were high. They walked straight over the edge of risky slopes, and their average attempt rate was 0.66. By their 10th week of walking, attempts decreased to 0.34.

Several lines of evidence indicate that the decrease in errors over weeks of locomotor experience reflects increased flexibility. First, infants' decisions became more closely geared to their actual abilities despite weekly changes in their bodies and skills. Their motor thresholds increased over weeks of belly crawling and decreased temporarily and then increased again over weeks of hands-and-knees crawling; thresholds decreased and increased yet again after they began walking. Thus, a risky slope one week could be safe the next week when the motor threshold was steeper; a safe slope for an experienced belly crawler could be impossibly risky when the infant began crawling on hands and knees. Second, the duration of infants' locomotor experience was a stronger predictor of their attempt rates on risky slopes than was their age at testing. Third, as shown by the open symbols on Figure 19.8, infants in the control group showed similar attempt rates at each matched session compared with the infants tested repeatedly. Finally, infants in cross-sectional studies show similar patterns of improvement when challenged with the novel slope task. For example, the 14-month-old walkers in Adolph's (1995) study showed comparable attempt rates to the infants in the longitudinal study when they were 14 months of age. Twelve-month-old crawlers, with approximately 15 weeks of crawling experience, behaved like the experienced crawlers tested longitudinally. Twelve-month-old walkers, with only 6 weeks of walking experience, behaved like the novice walkers tested longitudinally (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, in press; Ishak, Adolph, Lobo, Karasik, & Tamis-LeMonda, 2007). And 18-month-old walkers, with approximately 26 weeks of walking experience, behaved like the experienced walkers tested longitudinally (Lobo et al., 2007).

Alternative Means of Descent

Finally, locomotor experience was related to infants' discovery and use of varied alternatives for descending slopes (Adolph, 1997). On safe slopes, infants descended using their current locomotor methods on nearly every trial: belly crawling, crawling on hands and knees, or walking. But on risky slopes, alternative locomotor methods emerged over weeks of crawling and walking.

At first, infants dealt with recognizably risky slopes by avoiding the slope and waiting out the trial on the starting platform. After 13 weeks of crawling experience, prone descent strategies appeared. Hands-and-knees crawlers crept down on their bellies or slid spread-eagled, headfirst prone. Scooting and sliding in a sitting position appeared at about 13 weeks of crawling experience. Sometimes infants' use of sitting appeared deliberate: They sat at the edge and pushed themselves over the brink. Sometimes their use of sitting appeared serendipitous: While crawling down steep slopes, infants pushed backward so hard with their arms that they ended up in a sitting position, midslope, with their legs extended in a straddle split; eventually, they adopted the sitting position while still on the starting platform. Use of prone and sitting positions to descend slopes required infants to recognize existing strategies in their repertoires—belly crawling and sitting—as alternative means to achieve a goal.

Crawling and sliding backward feet first appeared at about 19 weeks of crawling experience. Backing was the most psychologically complex descent strategy. It required infants to execute an initial detour by turning away from the goal and then to proceed without visual guidance facing away from the goal. Most infants discovered backing in the course of trying to crawl down steep slopes. With their arms stiffly extended and legs tucked under their torsos, gravity pulled their bodies around until they were sideways or backward. Infants showed surprised at finding themselves in a backward position, sometimes exclaiming, "uh oh" and "oh no"; they crawled back up to the starting platform and peered down the slope in puzzlement. Eventually, they recognized backing as an alternative means and executed the position intentionally while still on the starting platform. Over weeks of walking, alternative descent strategies did not need to be rediscovered. Infants had only to recognize that walking was impossible on risky slopes and then draw on an existing alternative.

Limits on Flexibility

So far, we have provided evidence that infants behave flexibly in response to variable and novel conditions and that they acquire flexibility through everyday locomotor experience. In this section, we describe two kinds of limits on flexibility. Both limits involve the perceptual information that specifies possibilities for balance and locomotion. In the first case, developmental transitions in infants' posture—sitting, crawling, cruising, and walking—affect their ability to generate and use the relevant information for guiding action adaptively. During the period when infants are first mastering a new postural control system, they do not even know what the relevant information is. In the second case, limits on flexibility result from limits in the availability of perceptual information for surface substance. This limitation is critical and pervasive because the substantial properties of surfaces—friction, rigidity, mass, and so on—affect every physical encounter. In particular, novel variations in surface substance are not reliably specified by visual information from a distance, preventing infants from realizing that they are approaching a potential obstacle.

Specificity Between Developmental Transitions in Posture

Perhaps the most striking finding from the longitudinal study of infants descending slopes was that infants showed two learning curves, not one (Adolph, 1997). As illustrated in Figure 19.8, the same experienced crawlers who accurately perceived the limits of their ability to crawl down slopes attempted to walk down impossibly risky slopes when they stood up and faced the hills as novice walkers. Error rates on risky slopes were equally high in infants' first week of walking as they were in their first week of crawling (0.68 for each). They attempted to walk at the same rates as they attempted to crawl at each risky increment steeper than the motor threshold. Moreover, learning did not appear to be faster the second time around. Learning curves were parallel over weeks of crawling and walking.

Longitudinal observations provide one way to assess learning and transfer across developmental transitions in posture. An alternative approach is to keep age constant by testing infants in the same session in an earlier developing posture versus a later developing one. For example, in their first week of walking, infants were tested in six back-to-back trials on the risky 36-degree slope: two trials in their novice walking posture, two in their experienced crawling posture, and two in their novice walking posture.

Learning to learn was so specific to the earlier developing crawling posture that infants showed no evidence of transfer across consecutive trials. When started upright, infants marched straight over the edge of the 36-degree slope on two consecutive trials. Only moments later, when placed on the starting platform in their old, familiar crawling position, half the infants behaved like experienced crawlers and slid safely down. They had not forgotten or lost the alternative strategies in their repertoires; they simply did not know to use them. The other half of the infants pulled themselves up into a standing position and stepped over the brink as if they preferred to be hapless walkers rather than expert crawlers. When placed upright once again, infants attempted to walk despite the reminder that in their experienced crawling posture the slope was risky.

Specificity is not limited to the transition between crawling and walking postures or to locomotion over slopes. Infants also displayed specificity of learning when tested in an experienced sitting posture compared with a novice crawling posture at the edge of precipice (Adolph, 2000). All infants were 9.5 months of age, and all had more experience with sitting (M = 15 weeks) than with crawling (M = 6 weeks). As illustrated in Figure 19.9, the infants' goal was the same in both postures: to retrieve a toy at the far side of an adjustable gap spanning a deep precipice. An experimenter could vary the size of the gap from 0 to 90 centimeters in 2-centimeter increments by sliding a moveable landing platform along a calibrated track. Thus, infants had to decide whether they could lean forward while stretching an arm out to span the gap without falling into the precipice. Caregivers encouraged infants to cross the gap at every increment, and an experimenter spotted infants to ensure their safety if they fell over the edge.

As in the previous studies, a psychophysical procedure was used to determine relative risk levels for each infant in each posture. Motor thresholds ranged from 20 to 32 centimeters for sitting and from 2 to 18 centimeters for crawling, confirming the need for the normalization procedure. The thresholds for sitting were larger than infants' arm lengths, indicating that they leaned forward to retrieve the target.

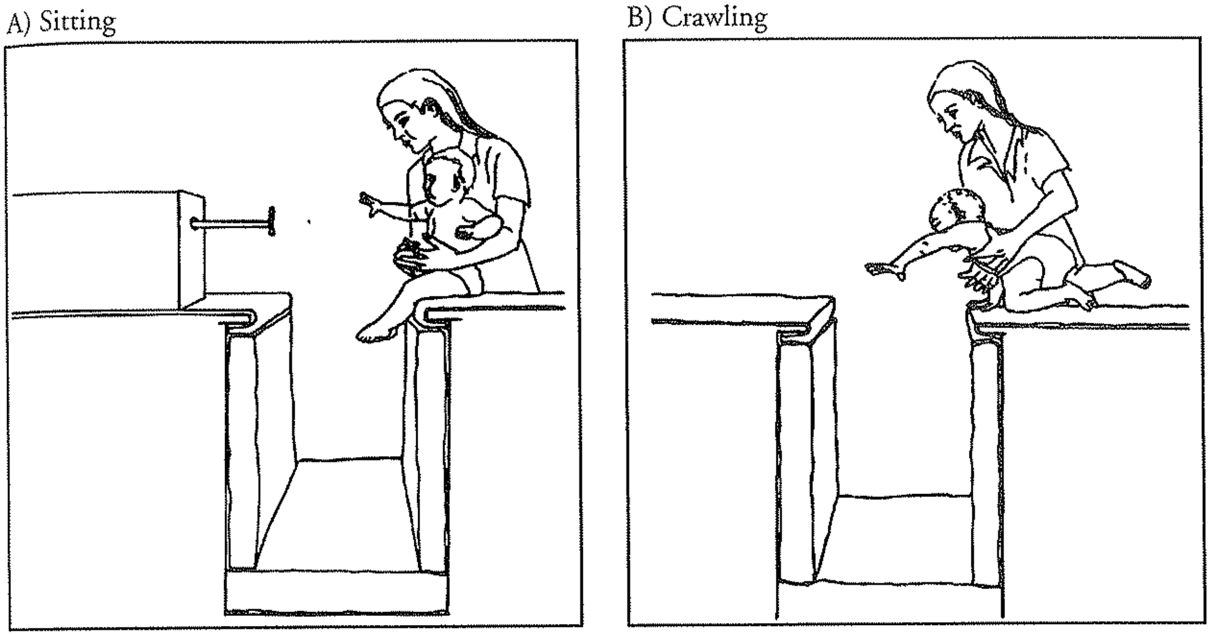


Fig. 19.9 Adjustable gap apparatus. Infants were tested in (A) experienced sitting and (B) novice crawling postures. Caregivers (not shown) stood at the far side of the platform encouraging infants to cross the gap. An experimenter (shown) followed alongside infants to ensure their safety and the gap was lined with padded cushions as an additional precaution. Reproduced with permission from Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 11,* 290–295. Wiley-Blackwell Publishing Ltd.

Infants with the smallest thresholds for crawling placed their hand straight into the tiny gap and fell. Infants with the largest thresholds fell as they leaned forward while stretching their arms across the gap.

Infants correctly attempted to span safe gaps in both postures. But at every risky gap increment, infants responded more adaptively in the experienced sitting posture compared with the novice crawling posture. In the sitting position at the edge of risky gaps, all infants closely matched their attempts to the conditional probability of success. Attempt rates dropped from nearly 1.0 at the threshold increment to nearly 0 on gaps 18 centimeters larger than the threshold. They were so frustrated by their inability to span the risky gaps that they turned their backs to the goal so that they would not have to look at the enticing toys for the duration of each 30-second trial. In the crawling position, infants grossly overestimated their ability to span the risky gaps. They fell on 61% of risky trials and attempt rates were >.50 at gaps 18 centimeters larger than the threshold. Although an experimenter called infants' attention to the gap on every trial, a third of the infants plunged into the 90-centimeter gap on repeated trials—as if they thought that they could crawl into thin air.

Additionally, infants showed evidence of specificity of learning between cruising and walking. Because both cruising and walking are upright postures, traditionally, researchers have assumed that cruising is merely an early form of independent walking. However, if cruising is merely a "practice" period before infants master upright balance without support from their arms, then experience cruising should lead to more adaptive motor decisions for walking. Using a variant of the gap apparatus and a psychophysical procedure to normalize risk levels, experienced 11-month-old cruising infants were tested in two postural conditions (Adolph, 2005; Leo, Chiu, & Adolph, 2000). In the condition relevant for cruising, infants were encouraged to cruise over a solid floor with an adjustable gap (0–90 cm) in the handrail

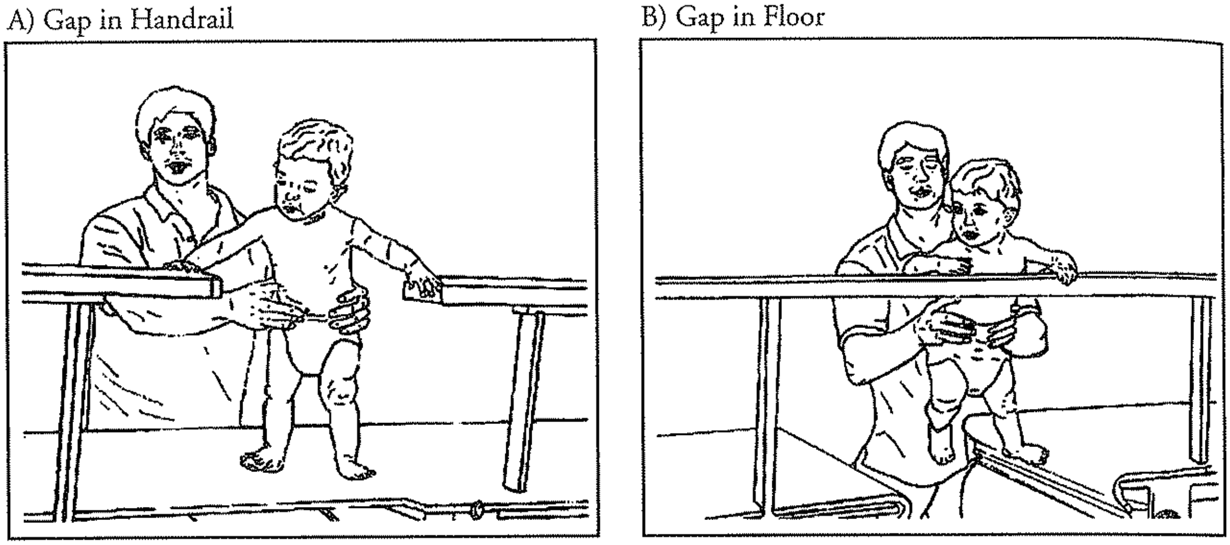


Fig. 19.10 Apparatus with adjustable gaps in handrails and floor. Infants cruised across (A) a gap in the handrail with a continuous floor and (B) a gap in the floor with a continuous handrail. Caregivers (not shown) encouraged infants from the far side of the platform, and an experimenter (shown) followed alongside infants to ensure their safety. Reprinted from Adolph, K. E., & Joh, A. S. (in press). Multiple learning mechanisms in the development of action. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind.* New York: Oxford University Press.

they held for support (Figure 19.10A). In the condition relevant for walking, infants were encouraged to cruise over a solid handrail with an adjustable gap (0–90 cm) in the floor beneath their feet (Figure 19.10B). In both conditions, an experimenter showed infants the gap at the start of each trial to ensure that they saw the size of the obstacle.

As in the previous studies, infants showed more adaptive responses in the condition relevant for their experienced posture. Infants attempted to cruise over safe gaps in the handrail, and on risky gaps, they crawled to the other side or avoided traversal. But when tested with gaps in the floor, infants attempted safe and risky increments alike as if they did not realize that they needed a floor to support their bodies. A second group of 11-month-old new walkers erred in both conditions (Adolph, 2005; Leo et al., 2000). Although they could take only a few consecutive steps before falling, new walkers no longer recognized how far they could travel between gaps in the handrail, and they did not yet recognize the gap in the floor as an impediment to locomotion.

Specificity Due to Information for Surface Substance

A second cause of limitations in flexibility is not due to developmental transitions in posture. Specificity can also result from the availability of perceptual information for variations in the ground surface. Flexibility in the face of variability and novelty requires perceptual information to specify the nature of the potential challenge. Variations in the surface layout (e.g., slant, bridge width, gap size, and elevation) are signaled by a multitude of reliable depth cues (binocular disparity, convergence, motion parallax, texture gradients, and so on). Thus, as described in the previous sections, visual information from a distance can alert infants to modify their locomotor patterns and exploratory behaviors as they approach a potential obstacle. Visual and tactile exploration generate information about possibilities for action, and experienced infants—like adults—are then in a position to respond adaptively.

In contrast, novel variations in the substance of the ground surface are not reliably specified by visual information from a distance. Friction ("slipperiness" in laymen's terms) and rigidity ("hardness") are resistive forces that emerge only when the body makes contact with the surface. The size of the resistive forces depends on the two contacting surfaces and their manner of contact. For example, the probability of slipping due to inadequate frictional forces depends on the flooring material (e.g., wood, carpet, or cement), the walker's footwear (rubber-soled sneakers, nylon socks, or bare feet), the current condition of the surfaces (dust, condensation, or wear and tear), foot velocity at contact, the angle of contact (feet planted squarely or with an initial heel contact), and so on.

The widespread belief that visual cues such as shine can serve as reliable signals for emergent forces such as friction is simply incorrect because the change in resistive forces does not exist before the two surfaces come into contact (Joh, Adolph, Campbell, & Eppler, 2006). Moreover, visual cues such as shine vary with changes in the overhead lighting conditions, viewing distance and angle, and the color of the ground surface—factors that do not affect the coefficient of friction (Joh et al., 2006). Without visual cues to prompt modifications in ongoing activity, even experienced walkers cannot detect novel changes in surface substance before they step onto the slippery or squishy surface. At that point, gait modifications become reactive rather than prospective. It is a case of too little perceptual information too late.

Several studies provide evidence for limitations on flexibility as walkers approach novel ground surfaces varying in rigidity and friction. In the most straightforward demonstrations, walkers approached a squishy or slippery obstacle on consecutive trials. On the first trial, the obstacle was novel. On subsequent trials, participants could learn from their previous encounters. For example, 15- to 39-month-old children and adults were encouraged to cross a walkway containing a large, squishy, foam pit (Joh & Adolph, 2006). The foam pit was so squishy that even the lightest infants fell if they attempted to walk over it; the foam pit was so large that infants were allowed to fall freely, landing face down in the sea of foam (Figure 19.11). An experimenter spotted the older children and adults to ensure

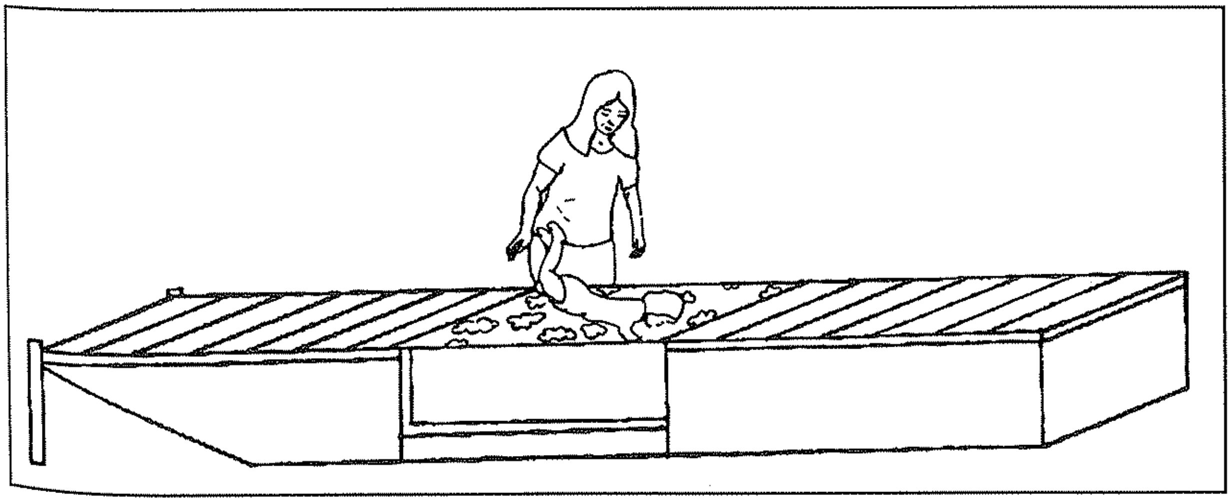


Fig. 19.11 Foam pit apparatus. Infants walked across a solid walkway containing a deformable foam pit to reach their caregivers (not shown). The foam pit was marked by changes in the color, texture, and pattern of the ground surface. The foam pit was large enough that the infants could fall into it freely without being caught. An experimenter (shown) followed the participants for safety and caught older children and adults if necessary. Reprinted from Adolph, K. E., & Joh, A. S. (in press). Multiple learning mechanisms in the development of action. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind.* New York: Oxford University Press.

their safety. Most important, the foam pit was marked by salient, visual cues: It was bumpy with rounded edges, like a couch cushion, and covered with a fabric that was distinct in color, texture, and pattern from the rest of the walkway.

Even the youngest infants were expert walkers (*M* walking experience = 12.56 weeks). As described in previous sections, by 15 months, infants demonstrate flexibility to novel changes in the surface layout (e.g., Adolph, 1995). By 16 months, infants take the substance of a handrail into account but only after they explore the handrail by touching it (Berger et al., 2005). The critical question here was whether participants would recognize the deformable surface as a potential obstacle. Would they display prospective gait modifications and exploratory behaviors as they approached the foam pit and select alternative means to avoid falling?

Results were clear. Every participant in all age groups fell straight into the foam pit on their first trial. Despite the change in the appearance of the ground surface, participants did not hesitate, alter their walking patterns, or explore the foam pit by touching it. Some infants and adults gasped or screamed after falling, indicating that the deformability of the foam pit was truly unexpected. In fact, most infants fell on multiple, consecutive trials before learning to avoid the foam pit. On average, 15-month-olds fell on 7.06 consecutive trials, 21- to 39-month-olds on 2.75 to 4.83 trials, and adults on only the first trial. On the trial where participants demonstrated learning, latency to step onto the foam pit, exploratory touches with the feet and hands, and shifts in position sharply increased, providing further corroboration that without visual cues from a distance, flexible responding is impaired.

A second study with a slippery obstacle replicated the pattern of results with 15-month-olds (Adolph, Joh, & Eppler, 2008; Joh, Adolph, & DeWind, 2005). A large patch of slippery Teflon replaced the foam pit. As in the previous experiment, the Teflon was visibly different from the rest of the walkway. It was white, shiny, and smooth (like ice), whereas the beginning and ending portions of the walkway were covered with a dark blue, matte, and textured carpet. Infants wore nylon stockings to increase the likelihood of slipping on the Teflon. Because infants fell backward as they slipped, an experimenter caught them to ensure their safety. As in the previous study, infants were oblivious to the novel friction condition on their first encounter. Despite the shiny, smooth surface of the Teflon, they walked straight onto the obstacle, slipped, and fell. Again, learning over subsequent encounters required multiple trials: Infants fell repeatedly, and hesitation, tactile exploration, and means–ends exploration did not increase until the first trial where they evidenced learning.

A second line of evidence for informational limitations on flexibility comes from studies where variations in surface substance and surface layout covaried. Even when perceptual information for surface substance was provided by tactile information underfoot, infants and adults relied primarily on visual information for surface layout. For example, 14-month-old walking infants were encouraged to descend a motorized walkway with adjustable slope (0–90 degrees) under low- and high-friction conditions (Adolph, Joh, & Eppler, 2008). On some trials, the entire surface of the walkway was covered with high-friction rubber and on other trials with low-friction vinyl. Thus, underfoot information about friction was available at the beginning of each trial as infants approached the slope from the flat starting platform. As in the previous slope studies, a psychophysical procedure was used to estimate infants' motor thresholds for each friction condition to equate the relative degree of risk. On average, infants' motor thresholds were 9.12 degrees steeper on high-friction rubber (*M* = 12.25 degrees) than on low-friction vinyl (*M* = 3.12 degrees). In fact, most infants had trouble walking over the low-friction surface when the slant was set to 0 degrees. Thus, in the low-friction condition, extremely shallow slopes could be impossibly risky.

Despite continuous, underfoot information about friction as they approached the brink of the slope, infants' motor decisions were based primarily on surface slant. On safe slopes shallower than the threshold increment, infants attempted to walk on nearly every trial. However, on risky slopes, attempt rates were higher in the low-friction condition at each risky increment. Errors were especially high on slopes slightly steeper than the threshold increment. For example, on slopes 10 degrees steeper than threshold, attempt rates were 0.39 in the high-friction condition and 0.65 in the low-friction condition. As further evidence that infants responded primarily to visual information for surface slant rather than friction, they attempted to walk on the same proportion of trials in both friction conditions when data were analyzed by the absolute degree of slope. Infants did not alter ongoing walking patterns or stop at the edge of the slope to engage in tactile exploration until they saw a relatively steep slope. Thus, they stepped straight onto shallow—but impossibly risky—low-friction slopes and fell. When the visual information for surface slant prompted infants to engage in additional exploratory activity at the brink, they correctly avoided attempts to walk down risky slopes and used an alternative sliding position instead.

Reliance on visual cues for surface layout is not limited to infants. When adults were asked to gauge possibilities for descending slopes, they relied on visual information for slant rather than underfoot information for friction (Joh, Adolph, Narayanan, & Dietz, 2007). They overestimated their abilities on low-friction vinyl by as much as 20 degrees (*M* = 9.18 degrees). Their errors had functional consequences because changes of 2 to 3 degrees were sufficient to cause adults to fall. Like the infants, however, adults showed more adaptive motor decisions when they obtained tactile information at the edge of the slope. When we allowed them to touch the low-friction slope with only half of one foot, their motor decisions matched their actual abilities (*M* difference = .09 degrees).

Conclusions: Flexibility in Development

Behavioral flexibility is so central to adaptive action that Eleanor Gibson (1994) called it a "hallmark of human behavior" (p. 71). Variability and novelty are endemic in everyday life. Happily, infants are excellent improvisers (Thelen, 1996). As we described in the previous sections, young infants display impressive flexibility in response to continually changing constraints on balance and locomotion. When faced with novel challenges such as steep slopes, narrow bridges, large gaps, and lead-weighted shoulder packs, experienced infants display adaptive motor decisions in sitting, crawling, cruising, and walking postures. Under variable conditions in the environment (variations in the degree of slant, bridge width, and so on) and in their own body dimensions and skills, infants scale their motor decisions to the actual possibilities for action. They alter their ongoing movements with subtle modifications in their locomotor patterns. They gather the requisite perceptual information with a sophisticated repertoire of exploratory movements. They discover new means to achieve their goals by intentionally testing various alternatives and by recognizing new strategies that arise in the course of trying to do something else.

For experienced infants, like adults, the only limits on flexibility appear to be informational. Novel variations in the substance of the ground surface (e.g., a deformable foam pit or a slippery slope) produce errors on the initial encounter. Flexibility may be specific to variations in the surface layout because changes in surface substance are not signaled by visual information from a distance. Infants can obtain adequate information about rigidity and friction from touching because physical contact with the obstacle creates resistive forces. However, without visual cues to prompt modifications in ongoing exploratory activity, infants do not realize the necessity of touching. The chain of exploratory behaviors is disrupted, and prospective control breaks down.

We also provided evidence in previous sections that flexibility is learned. Moreover, acquisition of flexibility requires a protracted period of experience. Infants require 10 weeks of crawling and walking experience, for example, before errors decrease below 0.50 on risky slopes and 20 weeks before errors decrease to about 0.10. What happens over those 10 to 20 weeks? Experience is not merely a euphemism for the passage of time. It is not the movement of the hands on a clock that leads to flexibility. It is the movement of infants' bodies. It is the thousands of steps, strides, turns, pauses, sways, slips, trips, and falls on the dozens of different surfaces and in the hundreds of different contexts that leads to flexibility. And during all those steps and sways and falls, infants do not amass an encyclopedia of knowledge about biomechanics and various surface properties. No list of facts or library of fixed solutions can give infants the wherewithal to cope with novelty and continual variability. Rather, infants learn how to discover the current limits and propensities of a familiar balance control system for acting in the current situation. They learn how to recognize the relevant perceptual information when it is available and how to generate the relevant perceptual information when it is not already available.

Finally, we have argued that learning to learn is nested in the larger time frame of development. The acquisition of flexibility is a tremendous developmental achievement because infants are learning about their new postural control system at the same time that the system is undergoing developmental change. That is, infants are learning about the relevant body parts for maintaining balance and propelling the body, the various muscle actions that perform compensatory swaying movements, the pivot points that their body rotates around, the sources of perceptual information that control postural and locomotor movements, and the features of the ground that support or hinder their movements—all at the same time that their bodies, skills, and environments are developing. The most extreme, qualitative developmental changes—transitions to new postural control systems—lead to specificity because the relevant body parts, muscle actions, pivot points, and so on are completely different.

Imagine building a robot that could learn to walk over various surfaces. Now imagine a robot whose body undergoes sudden growth spurts, whose strength and coordination change from week to week, and whose environment continually introduces novel surfaces. This sort of developing learning system is what developmental roboticists imagine building (Adolph, 2006). In fact, a developing learning system may be the optimal model of flexibility because the flux of developmental change may actually facilitate the task of learning to learn. If the system were static, then infants might be more inclined to learn simple facts about the environment and their bodies and skills—"this elevation is 20 centimeters high, my legs are 30 centimeters long, I'm a terrible walker"—and to form simple associations between them—"walking over a 20-centimeter elevation will result in a fall." Such static knowledge would be maladaptive because infants' legs will grow and strengthen and their skill levels will improve. Last week's cliff can become next week's stair. Last month's barrier can become next month's chair. Ongoing developmental changes may force infants to perceive possibilities for action in relative terms: How high is this elevation relative to my current leg length and walking skill? The flux of development may push infants to acquire the information-generating behaviors that allow relative comparisons. In one's wildest fantasies, the imaginary robot could learn to display behavioral flexibility with a host of postural control systems. This robot, still far in the realm of science fiction, would begin to approximate the developmental achievement of learning to learn in sitting, crawling, cruising, and walking postures.

References

Adolph, K. E. (1995). Psychophysical assessment of toddlers' ability to cope with slopes. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 734–750.

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251).

Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 11,* 290–295.

Adolph, K. E. (2002). Learning to keep balance. In R. Kail (Ed.), *Advances in child development and behavior* (Vol. 30, pp. 1–30). Amsterdam: Elsevier Science.

Adolph, K. E. (2005). Learning to learn in the development of action. In J. Lockman & J. Reiser (Eds.), *Action as an organizer of learning and development: The 32nd Minnesota Symposium on Child Development* (pp. 91–122). Hillsdale, NJ: Lawrence Erlbaum Associates.

Adolph, K. E. (2006, September). *Learning in the development of action.* Paper presented at the Proceedings of the Sixth International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems, Paris.

Adolph, K. E., & Avolio, A. M. (2000). Walking infants adapt locomotion to changing body dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1148–1166.

Adolph, K. E., Badaly, D., Garciaguirre, J. S., & Sotsky, R. B. (2008). *15,000 steps: Infants' walking experience.* Manuscript in preparation.

Adolph, K. E., & Berger, S. E. (2005). Physical and motor development. In M. H. Bornstein & M. E. Lamb (Eds.), *Developmental science: An advanced textbook* (5th ed., pp. 223–281). Mahwah, NJ: Lawrence Erlbaum Associates.

Adolph, K. E., & Berger, S. E. (2006). Motor development. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology: Vol. 2. Cognition, perception, and language* (6th ed., pp. 161–213). New York: Wiley.

Adolph, K. E., Eppler, M. A., Marin, L., Weise, I. B., & Clearfield, M. W. (2000). Exploration in the service of prospective control. *Infant Behavior and Development, 23,* 441–460.

Adolph, K. E., Gill, S., Lucero, A., & Fadl, Y. (1996, April). *Emergence of a stepping strategy: How infants learn to walk down hills.* Poster presented at the International Conference on Infant Studies, Providence, RI.

Adolph, K. E., & Joh, A. S. (in press). Multiple learning mechanisms in the development of action. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind.* New York: Oxford University Press.

Adolph, K. E., Joh, A. S., & Eppler, M. A. (2008). *Infants' perception of affordances of slopes under high and low friction conditions.* Manuscript in preparation.

Adolph, K. E., Tamis-LeMonda, C. S., Ishak, S., Karasik, L. B., & Lobo, S. A. (in press). Locomotor experience and use of social information are posture specific. *Developmental Psychology.*

Adolph, K. E., Vereijken, B., & Denny, M. A. (1998). Learning to crawl. *Child Development, 69,* 1299–1312.

Adolph, K. E., Vereijken, B., & Shrout, P. E. (2003). What changes in infant walking and why. *Child Development, 74,* 474–497.

Berger, S. E., & Adolph, K. E. (2003). Infants use handrails as tools in a locomotor task. *Developmental Psychology, 39,* 594–605.

Berger, S. E., Adolph, K. E., & Lobo, S. A. (2005). Out of the toolbox: Toddlers differentiate wobbly and wooden handrails. *Child Development, 76,* 1294–1307.

Bernstein, N. (1996). On dexterity and its development. In M. L. Latash & M. T. Turvey (Eds.), *Dexterity and its development* (pp. 3–244). Mahwah, NJ: Lawrence Erlbaum Associates.

Bril, B., & Ledebt, A. (1998). Head coordination as a means to assist sensory integration in learning to walk. *Neuroscience and Biobehavioral Reviews, 22,* 555–563.

Capute, A. J., Shapiro, B. K., Palmer, F. B., Ross, A., & Wachtel, R. C. (1985). Normal gross motor development: The influences of race, sex and socio-economic status. *Developmental Medicine and Child Neurology, 27,* 635–643.

Frankenburg, W. K., Fandal, A. W., Sciarillo, W., & Burgess, D. (1981). The newly abbreviated and revised Denver Developmental Screening Test. *Journal of Pediatrics, 99,* 995–999.

Garciaguirre, J. S., Adolph, K. E., & Shrout, P. E. (2007). Baby carriage: Infants walking with loads. *Child Development, 78,* 664–680.

Gibson, E. J. (1994). Has psychology a future? *Psychological Science, 5,* 69–76.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development.* New York: Oxford University Press.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Gill-Alvarez, S. V., & Adolph, K. E. (2005, April). *Flexibility in infant skill acquisition: How infants learn a stepping strategy.* Poster presented at the meeting of the Society for Research in Child Development, Atlanta, GA.

Harlow, H. F. (1949). The formation of learning sets. *Psychological Review, 56,* 51–65.

Ishak, S., Adolph, K. E., Lobo, S. A., Karasik, L. B., & Tamis-LeMonda, C. S. (2007, March). *Experienced crawlers and novice walkers descending slopes.* Poster presented at the meeting of the Society for Research in Child Development, Boston, MA.

Joh, A. S., & Adolph, K. E. (2006). Learning from falling. *Child Development, 77,* 89–102.

Joh, A. S., Adolph, K. E., Campbell, M. R., & Eppler, M. A. (2006). Why walkers slip: Shine is not a reliable cue for slippery ground. *Perception & Psychophysics, 68,* 339–352.

Joh, A. S., Adolph, K. E., & DeWind, N. K. (2005, November). *Learning from slipping and falling.* Poster presented at the meeting of the International Society for Developmental Psychobiology, Washington, DC.

Joh, A. S., Adolph, K. E., Narayanan, P. J., & Dietz, V. A. (2007). Gauging possibilities for action based on friction underfoot. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 1145–1157.

Kuczmarski, R. J. (2000). *CDC growth charts: United States. Advance data from vital and health statistics; no. 314.* Hyattsville, MD: National Center for Health Statistics.

Lampl, M., Veldhuis, J. D., & Johnson, M. L. (1992). Saltation and stasis: A model of human growth. *Science, 258,* 801–803.

Lee, D. N. (1993). Body-environment coupling. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge* (pp. 43–67). Cambridge: Cambridge University Press.

Leo, A. J., Chiu, J., & Adolph, K. E. (2000, July). *Temporal and functional relationships of crawling, cruising, and walking.* Poster presented at the International Conference on Infant Studies, Brighton, England.

Lobo, S. A., Koren, A., Ishak, S., Karasik, L. B., Adolph, K. E., & Tamis-LeMonda, C. S. (2007, March). *Friction underfoot affects infants' ability to cope with slopes.* Poster presented at the meeting of the Society for Research in Child Development, Boston, MA.

Reed, E. S. (1982). An outline of a theory of action systems. *Journal of Motor Behavior, 14,* 98–134.

Siegler, R. S., Adolph, K. E., & Lemaire, P. (1996). Strategy choice across the life span. In L. Reder (Ed.), *Implicit memory and metacognition* (pp. 79–121). Mahwah, NJ: Lawrence Erlbaum Associates.

Stevenson, H. W. (1972). *Children's learning.* New York: Appleton-Century-Crofts.

Thelen, E. (1996). The improvising infant: Learning about learning to move. In M. R. Merrens & G. G. Brannigan (Eds.), *The developmental psychologists: Research adventures across the lifespan* (pp. 21–36). New York: McGraw-Hill.

von Hofsten, C. (1993). Prospective control: A basic aspect of action development. *Human Development, 36,* 253–270.

von Hofsten, C. (2003). On the development of perception and action. In K. J. Connolly & J. Valsiner (Eds.), *Handbook of developmental psychology* (pp. 114–140). London: Sage.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences, 8,* 266–272.