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Flexibility and Specificity in Infant Motor Skill Acquisition

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**INTRODUCTION: TRANSFER IN MOTOR SKILL ACQUISITION**

A long-standing, unsolved puzzle in motor skill acquisition is the problem of transfer: How does experience in a familiar motor context facilitate performance in a novel situation? Since Thorndike’s (1906; Thorndike & Woodworth, 1901) classic work at the turn of the century, researchers have assumed that the solution to the puzzle can be found in a search for identical elements. More specifically, the traditional assumption is that transfer depends on the extent to which elements of the training context—the nature of the environmental stimulus, the patterns characterizing the motor response, or the mental representations that support motor knowledge—are similar to elements of the performance context (e.g., Anderson & Singley, 1993). Concepts like stimulus generalization, motor equivalence, and learning via analogous mental elements have each had their heyday (Adams, 1987). However, after nearly 100 years of study, researchers still lack a satisfactory theory of transfer in motor skill acquisition. One of the impediments to progress is that the identical elements approach and the experiments that stem from it cannot, in principle, explain adaptive, functional motor skills. The notion of identical elements in simple associative learning is far too static and narrow to account for the step-to-step, moment-to-moment variability that characterizes real, everyday motor skills.

Motor skill in the natural environment involves knowing which actions are possible for the given situation. It requires a continual, online decision-
making process because the everyday environment and one's physical capabilities are continually changing. Both factors (i.e., properties of the environment and physical abilities of the individual) must be considered together in a relationship that is dynamic rather than fixed. The same slippery slope may be perfectly safe when walking with the arms free and wearing shoes with a sure grip, but completely impossible while carrying a heavy load or wearing leather-soled shoes. Changing the distribution of the load, modifying step length, even raising or lowering the arms change possibilities for action because such step-to-step variations change the physical constraints on keeping balance. Thus, an identical elements approach to transfer based on accretion of static facts about stimuli or responses cannot be sufficient for explaining adaptive control of action. The same elements can have different movement consequences depending on the current status of the actor–environment relationship.

In this chapter, we describe a fresh approach to tackling the old problem of transfer. The question remains of when and how experience facilitates performance in a novel motor context. However, the old search for identical elements has been reformulated into a new program of research aimed at understanding the process of online decision making in infant motor skill acquisition. The ability to generate adaptive solutions in a dynamic and variable real world requires flexibility of action. Motor skills show flexibility when the individual can cope adaptively across a wide range of novel contexts. On the flip side, motor skills show specificity when adaptive action is limited to a narrow range of contexts. As described shortly, the broader focus on flexible, adaptive action leads to a very different way of understanding experience-related changes. Rather than acquiring a repertoire of stimulus–response bonds or any sort of static representations for controlling action, infants may acquire the tools for online decision making. The key to learning and transfer of motor skill may be the willingness to plan movements adaptively, from moment to moment and task to task.

The study of flexibility in infants is particularly illustrative because transfer of learning is nested within a larger context of developmental change. Infants’ bodies change dramatically over the first 2 years of life and their effective environment expands exponentially. In the midst of all this flux, new skills appear with remarkable regularity and abundance—reaching, sitting, crawling, walking, etc. Changes in the biomechanical constraints of their growing bodies and physical propensities change possibilities for action and introduce infants to new situations. Infants’ everyday life poses continual tests of transfer because they must use their current motor skills to respond adaptively to new environmental properties and tasks. However, unlike any traditional test of transfer, babies must also respond adaptively to the same situations and tasks at different periods of development using very different postural control systems. The same environmental property (e.g., a squishy surface, a sloping floor, or a cliff) can have very different consequences for action when a baby is mastering head and trunk control, able to sit up alone, crawling on all fours, or able to walk independently.

OVERVIEW

This chapter describes a program of research aimed at understanding flexibility in infant motor skill. Our primary goal is to illustrate a new way of addressing the old problem of transfer in motor skill acquisition.

Conceptually, both transfer and flexibility deal with novelty. Transfer is the extent to which experience in a familiar motor context facilitates performance in a novel situation. Similarly, flexibility is the extent to which actions are adapted to novel and variable local conditions. Flexibility implies adaptation to a wide range of novel motor contexts. Specificity, on the other hand, implies adaptive responses only in a narrow range of motor contexts, when adaptive action is limited to particular environmental situations, motor responses, or body parts. The next section defines flexibility in more detail, why it is so central for functional motor skills, and how it is achieved in online decision making.

Traditional studies of transfer in motor skill are limited primarily to adult populations performing specialized motor tasks such as tapping out Morse Code (Bryan & Harter, 1897; Bryan & Harter, 1899), typing (Book, 1925), piano playing (Shaffer, 1980), and flying an airplane (Adams & Huford, 1962); or to sport skills such as skiing (Emmerik, Brinker, Vereijken, & Whiting, 1989), perfecting a golf swing (Adams, 1985), and throwing beanbags at targets (Kerr & Booth, 1978) and basketballs through hoops (Wallace & Hagler, 1979). Outcome measures are typically limited to success/failure and speed/accuracy. In contrast, our studies of flexibility focus on more everyday motor skills (e.g., locomotion over novel terrain) in infants at various stages of motor development. We exploit the variability endemic on both sides of the actor–environment equation and present a wide array of outcome measures designed to provide insights into the online decision-making process. The fourth section shows that the study of flexibility in infants is feasible. Indeed, research paradigms that focus on flexibility may better reflect adaptive responses to novelty under real world constraints than tasks designed to test simpler models of skill acquisition and transfer. Moreover, this section shows that infants are capable of impressive displays of flexibility.
An important conceptual difference between the constructs of transfer and flexibility concerns the role of learning. Transfer, of course, requires learning by definition. In contrast, flexibility does not require learning by definition; in principle, skills could be highly flexible from the start. However, that turns out not to be the case. In the fifth section, we provide empirical evidence that flexibility, like transfer, depends on experience. The tools for online decision-making are the heart of what infants must learn for adaptive action. Additionally, we describe cases where learning does and does not transfer. As outlined later, learning is both remarkably general and surprisingly specific.

In the sixth section, we propose possible mechanisms that may underlie this sort of learning in a system that is itself continually changing. We focus on what infants do and do not learn that promotes flexibility, and on ways in which the developmental context may affect how knowledge is acquired. Finally, in the last section, we conclude with implications of this research program on flexibility for understanding the problem of transfer in motor skill acquisition.

We illustrate each section of the chapter by drawing on recent research from our laboratories and others where infants were challenged to adapt their newly developing locomotor skills to variations in the ground surface. The basic experimental paradigm is to observe the conditions under which infants respond adaptively to potentially risky ground and to examine the processes underlying their perceptual judgments and motor responses.

HALLMARKS OF ADAPTIVE ACTION AND THE ROLE OF FLEXIBILITY

Skilled actions require flexibility. They cannot be performed in the same way over and over because the biomechanical constraints on movement are continually changing (Bernstein, 1967, 1996; Lashley, 1960; MacKay, 1982). The everyday environment is variable and unpredictable and full of novel situations. The functional, physical propensities of the body change from moment to moment (e.g., raising an arm changes the subtle biomechanics of maintaining balance). Even the most automatized movements such as walking and talking must be continually modified to suit the current demands of the particular motor context. Flexibility refers to the extent to which ongoing movements are adapted to novel changes in local conditions. It is what makes a basketball star able to change his plan mid-jump to land a basket or what makes ordinary pedestrians able to modify their gait or select a new path to navigate a tricky patch of ground. It is the adaptive nature of true motor skill rather than the rote reproducibility.

4. FLEXIBILITY AND SPECIFICITY

Prospectivity

Adaptive action has three important characteristics. First, skilled movements must be prospective and planful rather than merely responsive (Hofsten, 1993; Lee, 1993). Prospective control means lifting a leg to clear the curb, rather than recovering balance after tripping. Unexpected, unique motor problems demand online solutions. Because we cannot know all of the relevant parameters ahead of time, flexibility requires exploratory movements to generate the requisite information for planning adaptive responses. Typically, exploration involves subtle movements of eyes, head, and body, and results in multimodal and redundant sources of information. Infants provide a revealing test case for studying prospective control because their exploratory and preparatory movements tend to be larger and more easily observable than those of adults.

Affordance Relationship

Second, adaptive action is relational. It depends on the match, or fit, between the current properties of the environment and the current status of the person's physical abilities—what J. J. Gibson (1979) termed affordances (see also Adolph, Eppler, & Gibson, 1993b; Warren, 1984). Walking, for example, is possible only if the ground surface is sufficiently clear of obstacles to permit safe passage, extensive enough to keep balance, rigid enough to support the body's weight, flat enough to keep the body upright, with the necessary friction to counteract shearing forces, and so on (Stoffregen & Riccio, 1988). When there is a mismatch or lack of fit between environmental properties and the person's physical capabilities, normal walking is impossible. We must stop in our tracks, choose a different route, modify walking gait, or select an alternative method of locomotion.

This relational aspect of motor skill is especially important during infancy because babies' bodies and physical constraints on balance control change so dramatically. From birth to 2 years of age, infants' height nearly doubles and their weight more than quadruples (Palmer, 1944; Shirley, 1931; Snyder, Spencer, Owings, & Schneider, 1973). Recent research shows that infants' body growth is episodic, not continuous (Lamp, 1983, 1993; Lamp, Veldhuis, & Johnson, 1992). Height, for example, remains at a constant plateau for days or weeks on end, then surges 5 cm to 2 cm overnight. As babies' bodies become slimmer and more maturely proportioned, their center of mass lowers from the bottom of the sternum to slightly above the belly button (Palmer, 1944). Such changes in infants' body proportions combined with variations in the ground literally change the physics of keeping balance in sitting, crawling, and walking postures.
Variety of Means

Finally, adaptive action involves a variety of means to achieve similar functional outcomes. On a muscle level, variability is endemic in movement. Because of the viscoelastic properties of the muscles and joints and the inertial forces resulting from ongoing movements, identical muscle forces can generate different outward movement patterns (Bernstein, 1967, 1996). For example, the same muscle forces in the arm generate different movements when the arm is at the side of the body, overhead, or swinging. Reciprocally, the same movement pattern can be performed with different underlying muscle forces (e.g., using only biceps to hold the arm parallel to the floor versus cocontracting biceps and triceps to do the same thing). Furthermore, on a behavioral level, flexible variety of means requires more than motor equivalence or response generalization (MacKay, 1982). Movements must be truly creative (Bruner, 1972, 1973). The changeable nature of infants’ bodies, skills, and environments requires that the right movements be selected at the right time. Variety of strategic options is necessary for such a selection process. By observing skill acquisition in infants, we may discover the origins of variable means: where new movement strategies come from, factors that influence strategy selection, and how variety of means is maintained in infants’ repertoires.

In sum, flexibility allows infants to cope with a varying body in a varying world by providing the wherewithal to predict the consequences of future movements on a step-to-step basis. Thus, an appropriate research program for studying flexibility in infant skill acquisition must incorporate variation on both sides of the infant–environment equation and maintain the nested structure of experience-related changes—during the course of a single trial, across trials within the session, and across the course of development.

STUDYING FLEXIBILITY IN INFANT LOCOMOTION

Our research focused on tasks where babies must cope with potentially risky ground surfaces. In particular, we challenge babies to descend slopes and stairs, and to cross cliffs and gaps because such changes in the depth of the ground surface provide good motivation for adaptive responding. Falling downward is aversive for infants (they typically fuss after falling) and they are usually loathe to err on the side of recklessness.

This section presents examples of two experiments designed to examine flexibility of responding. In the first study, walking infants were asked to cope with locomotion down shallow and steep—safe and risky—slopes (Adolph, 1995). In the second study, toddlers coped with locomotion down slopes while loaded with lead-weight shoulderpacks (Adolph & Avolio, 2000). As described next, slopes offer an ideal condition for studying flexibility in infant locomotor skill acquisition for several reasons.

The Slope Task

Transfer to a Novel Motor Task. A primary reason for observing infants’ behavior on slopes is to examine how and when infants display flexibility in a novel motor context. Viewing and navigating sloping ground are relatively novel activities for young infants. Although babies have many opportunities to view objects slanting in depth especially around a vertical axis, they rarely see the ground surface slanting downward away from the line of sight around the horizontal axis (Eppler, Adolph, & Weiner, 1996). Most parents in our studies report that they do not allow their young babies to negotiate playground slides independently or to walk down sloping driveways, wheelchair ramps, or hills without an adult’s help.

More than half a century ago, McGraw (1935) exploited the novelty of sloping ground to examine how learning and development affect changes in infants’ crawling and walking patterns. Fueled by the nature/nurture debate of the day, McGraw’s aim was to compare the gait patterns of one infant who received daily training on slopes with the gait patterns of his identical twin for whom the slope task would be truly novel. She reasoned that any differences between the twins would be the result of learning. Unfortunately, the untrained “control” twin refused to cooperate and sat at the base of the slopes weeping. Like McGraw, we appreciate the novelty of slopes as a fruitful testing ground for studying motor learning and development. However, with our focus on flexibility, we aimed to test the adaptiveness of infants’ responses rather than biomechanical changes in their gait patterns. We reasoned that if flexibility requires learning, adaptive responses should be linked with infants’ locomotor experiences. If such learning transfers across various types of ground surfaces and motor contexts, then locomotor experience outside the laboratory (e.g., on flat ground) should predict the adaptiveness of their responses on novel slopes.

The Biomechanical Relationship Between Surface Slant and Body Propensities. A second reason for observing infants’ behavior on slopes is that changes in surface slant have serious biomechanical consequences for balance control during stance and locomotion. Steeper hills are more difficult because more muscle torque is required to counteract destabilizing forces. Coping with downhill slopes is especially difficult because of the configuration of the body relative to the ground surface and the pull of gravity. Toddlers’
feet (or crawlers’ hands) are at a downward angle, decreasing the base of support. The muscles at the back of the supporting limbs must work to keep the body in an upright position and to brace it against rotating forward. With each walking or crawling step, the moving limb must straighten before contacting the ground surface resulting in a prolonged period with only one foot or hand on the ground. This is especially serious for babies' locomotion because they have trouble keeping balance with only one foot (or one hand and knee) on the floor. The already compromised supporting limb must bend rather than straighten to exert force. Such eccentric muscle actions require more muscle strength for supporting body weight and maintaining balance than a straight limb. The vertical acceleration of the center of mass is negative when the moving foot or hand contacts the surface, meaning that infants are falling downward into each step. This exacerbates the already thorny problem of keeping balance during single limb support. Steeper slopes increase the vertical distance that the body falls. If infants lose control, their hands are in an awkward position to protect their heads.

Reciprocally, differences in infants’ physical attributes interact with degree of slant. Developmental changes in physical growth and locomotor experience affect changes in body dimensions, muscle strength, and balance control. These variables, in turn, affect the biomechanics of locomotion down slopes. Babies with more mature body dimensions, more muscle strength, and more advanced gait patterns on flat ground have greater wherewithal to walk or crawl down steeper slopes. More mature body dimensions such as a lower center of mass mean that the body can sway farther forward and backward before toppling over. Like a top-heavy bookcase, top-heavy babies tip over sooner and with less provocation than more maturely proportioned, cylindrically shaped ones. Stronger legs (or arms in the case of crawlers) give greater stability during single leg/arm support and allow infants to generate more muscle torque to counteract destabilizing torque if their body begins to rotate too far forward or backward. More advanced gait patterns on flat ground give infants more options to adapt gait to the slant of a hill. An efficient strategy for coping with downhill slopes, for example, is to shorten step length and decrease step velocity to minimize the vertical distance that the body falls at each step.

Information for Prospective Control. A third reason why slopes provide a good test case for studying flexibility is that so much multimodal and redundant information is available for prospective control of locomotion. Obtaining the appropriate information requires babies to produce a variety of exploratory movements, allowing us to observe the process of prospective control firsthand. Infants can obtain visual information about surface slant, the height of the drop-off, and visible surface texture by peering over the brink of the hill. Movements of the head and body in depth generate motion parallax and cause changes in visual texture gradients such that the optic texture elements farther away from infants’ eyes are denser and flow more quickly across the optic array than the closer elements. Infants can obtain both visual and mechanical information about their own postural stability relative to the slope as they sway back and forth or take small steps to approach the hill. As their bodies sway forward in the course of quiet stance or locomotion, texture elements in the optic array stream backward. As their bodies sway backward, optic texture elements stream forward. The speed of body sway is specified by the speed of the optic flow. Tactile information about surface slant and friction is available by probing the slope with a hand or foot. Most commonly, infants straddle the brink of the slope with their feet or hands and sway back and forth. These movements are extremely rich sources of information about the properties of the ground surface relative to infants’ own physical propensities. They generate torque around the ankles or wrists and shearing forces between the extremities and the ground surface, and at the same time, generate concomitant changes in the speed and direction of optic flow.

Variety of Means. A final virtue of the slope task is that it allows observation of a flexible variety of means. As McGraw (1935) described in her classic co-twin study, there are multiple options for responding adaptively to variations in downhill slopes: walking, crawling on hands and knees, sliding down headfirst prone (like Superman), sliding or crawling backward feetfirst with the head pointing away from the direction of travel, sliding down in a sitting position, and avoiding descent entirely. Moreover, infants can modify walking and crawling gait with subtle changes in locomotor strategy. They can minimize the vertical distance that their body falls by decreasing step length and/or step velocity with increase in degree of slant. They can augment postural control via a form of tool use by holding onto a rafter, banister, or adult for additional support. Or, they could modify the joint angles characteristic of normal walking or crawling so as to keep the body in a more upright configuration, limit the range of forward and backward postural sway, or bear the brunt of destabilizing forces at stronger joints such as knees rather than ankles.

How Toddlers Cope With Locomotion Down Slopes

In our initial work, we found that 14-month-old walking infants differentiated 10°, 20°, 30°, and 40° slopes by their method of locomotion and exploratory activity (Adolph, Eppler, & Gibson, 1993a; Eppler et al., 1996).
The study described in this subsection introduced a new, modified psychophysical staircase procedure for testing infants over dozens of trials and over a continuous range of slopes (Adolph, 1995). The aim was to assess the accuracy of their judgments about safe and risky slopes and to examine the online process underlying their decisions.

Age-Matched Control Design. Thirty-one infants (17 boys and 14 girls) participated in the study. All were 14 months old ± one week and could walk over a 9-foot path independently, but walking experience, walking skill, and body dimensions varied freely. This age-matched control design allowed comparisons between individuals for the developmental variables of interest, while providing a crude control for general age-related changes.

Walking experience and walking skill varied widely among infants. Walking experience ranged from 10 days to 137 days (M = 77 days). Ten infants had prior experience going down playground slides and 17 had prior experience descending stairs independently. Four toddlers had experienced a serious fall after walking onset requiring medical attention.

Walking skill on flat ground was assessed using a footprint method of gait analysis (Adolph et al., 1996, April). Babies walked over a long strip of butcher paper with inked tabs on the soles of their shoes, leaving behind a trail of footprints. Coders used a coordinate grid to identify the x-y coordinates of each heel and toe placement and a computer program transformed the coordinates into kinematic measures of walking skill (linear distance between consecutive steps, lateral distance between the feet, dynamic base of support, and amount of in- or out-toeing). Step lengths ranged from 16 cm to 31 cm, step width from 6 cm to 18 cm, base of support from 100° to 156°, and foot rotation from −14° to 27°. More mature gait patterns are characterized by longer step lengths, smaller step widths, a base of support approaching 180°, and toes pointing straight ahead closer to 0°.

In contrast to the wide range in experience and walking skill, there was a relatively narrow range in infants’ body dimensions. Height ranged from 73 cm to 83 cm, weight from 8 kg to 13 kg, head circumference from 45 cm to 50 cm, leg length from 31 cm to 36 cm, and Ponderal Index (an overall chubbiness index) from 1.8 to 2.4.

Sloping Walkway. A mechanized sloping walkway was constructed to vary the slant of the ground surface along a continuous scale (see Fig. 4.1). The walkway was composed of three wooden sections, each 91 cm long x 84 cm wide, connected by piano hinges: a stationary flat starting platform, a middle sloping section, and an adjustable flat landing platform. A hydraulic pump under the landing platform changed its height from 22 cm to 75 cm, causing the middle section to slant from 0° to 36° in 2° increments. The walkway was covered with soft carpet to cushion infants’ falls and safety nets along the sides provided protection from tumbling off the sides of the ramp. All trials were videotaped for later analyses.

Psychophysical Staircase Procedure. The infants’ task was to decide whether to walk, slide, or avoid going down slopes. The shallowest slopes were safe for every baby to walk down. The steepest slopes were risky for even the most expert walkers. The viability of the intermediate range of slopes depended on each infant’s level of walking skill. Babies began each 60s trial in a standing position on the starting platform. Parents stood at the far side of the landing platform and encouraged their babies to come down using toys and Cheerios as enticements. An experimenter followed alongside infants to ensure their safety. Adults never instructed infants to be careful or to use a particular method of locomotion for traversal.

The experimenter used a modified psychophysical staircase procedure (Adolph, 1995) to estimate the steepest slope each infant could walk down. A staircase procedure is a classic method in psychophysics (Cornsweet, 1962) for estimating a threshold or change point—in this case, a motor threshold rather than a perceptual one—while minimizing the total num-
falling and others could manage terrifically steep ones. Measures of walking experience and walking skill on flat ground predicted infants’ slope boundaries, attesting to the validity of the estimates derived from the staircase procedure. More experienced, skillful walkers on flat ground were also better walkers on slopes. Body proportions were not related to slope boundaries.

**Online Decision Making About Relative Risk.** To equate relative degree of risk across babies with such different walking abilities, we normalized the definition of safe and risky slopes to each infant’s slope boundary. By definition, slopes shallower than infants’ boundaries were safe and slopes steeper than their boundaries were increasingly risky. A “go ratio” indexed the accuracy of infants’ perceptual judgments about whether slopes were safe for walking: (successes + failures)/(successes + failures + refusals). In the numerator are attempts to walk and in the denominator are both attempts and refusals to walk. (Note, the inverse “no-go ratio” yields the same information). Because successes were rare on risky slopes by definition, the range in go ratios at these increments depended on the difference between failures and refusals. The ratio could vary freely from 0 to 1 on all slopes except the boundary slope, where the ratio was ≥ .67 by definition. Perfectly adapted decisions would be indicated by scaling perceptual judgments to infants’ actual ability (i.e., matching the probability of attempts to the conditional probability of success). Babies should display high go ratios, near 1.0, on safe slopes where the probability of successful walking was high, and low go ratios, near 0, on risky slopes where the probability of success was low. Thus, the slope boundary served as a measure of infants’ actual ability to walk down slopes, the go ratio served as a measure of the accuracy of their prospective control of locomotion, and the normalization of go ratios to slope boundaries served as a measure of whether their judgments reflected appreciation of the relationship between their own abilities and environmental properties.

On average, infants’ judgments were impressively adaptive. They attempted to walk down safe slopes and refused to walk down increasingly risky ones. Figure 4.3a shows go ratios normalized by relative degree of risk to each infant’s slope boundary. The boundary slope is denoted by 0 on the x-axis, slightly easier and slightly harder slopes by ± 5°, slopes in an intermediate range by ± 13°, and impossibly risky slopes by ≥ +18°. Go ratios decreased steadily from .94 at slope boundary to .11 at +18° and the shape of the go ratio curve closely matched the probability of success. Prospective control involved perceiving the fit between infants’ own physical capabilities and the properties of the slope. This sort of prospective control is all the more impressive given the variability in degree of slant from trial to trial. Infants’ decisions about whether slopes were safe for

![Image of a table and diagram illustrating the psychophysical staircase procedure.](image-url)

**FIG. 4.2.** Typical protocol from Baby #27 to illustrate the psychophysical staircase procedure. Each trial was coded online as success, S (walked safely), failure, F (tried to walk but fell), or refusal, R (slid down or avoided going). The experimenter presented steeper slopes after successful trials and shallower slopes after failures or refusals to estimate slope boundary to a 67% criterion. Shaded row indicates the boundary slope.
walking had to be based on information they obtained on the starting platform at the beginning of each trial.

The Informational Basis for Infants’ Decisions. Infants’ activity on the starting platform provided the basis for inferences about the process of prospective control of locomotion. By definition, exploratory movements occurred earlier in the trial than the behaviors used to index perceptual judgments. Trials began only after infants made visual contact with the slope. Parents and the experimenter called infants’ attention to the slope and to an attractive lure on the landing platform. Then the experimenter released the babies on the starting platform. For the next 60s, babies had to decide on their own whether and how to descend. Coders scored latency to begin descent as a crude index of visual exploration. Brief latencies reflect quick glances and long latencies reflect longer looking times. Duration of touching slopes was an index of haptic exploration. Coders scored touches only when infants stopped forward locomotion and probed the sloping surface with hands or feet. To examine how infants selected an appropriate descent strategy, coders scored babies’ shifts in position. Avoidance required no shifts and the various sliding positions required only one shift. Thus, multiple shifts in position (e.g., standing to back, to standing to prone = 3 shifts) reflected a means–ends search for an alternative method of locomotion to descend. In principle, duration and type of exploratory activity were independent of infants’ slope boundaries and go ratios. That is, refusal to walk did not require prolonged exploration (babies could immediately choose an alternative sliding position for descent), and successes and failures did not prohibit prior exploration (babies could engage in prolonged exploration of any type then walk over the brink nonetheless).

Overall, infants’ spontaneous exploratory activity neatly mirrored their perceptual judgments. Go ratios decreased and exploratory activity increased with relative degree of risk (compare Fig. 4.3a with Figs. 4.3b, c, and d). On average, babies hesitated longer, touched more, and displayed more shifts in position on increasingly risky slopes. Latencies ranged from 0.1s to 60.0s, but were generally very short (Mean = 0.2s). On safe slopes, infants walked right down after only a brief glance at the surface as the experimenter released them on the starting platform. Long latencies were restricted to riskier slopes where the probability of falling increased. During the time babies hesitated, they peered over the brink of the slope, swayed backward and forward in place, took steps on the starting platform, touched slopes, and tested various sliding positions. The information obtained during the latency period informed infants’ decisions about whether and how to descend. If toddlers hesitated, even for a brief moment, they were more likely to refuse to walk than if they descended without hesitation (9% refusals on trials ≤ 0.2s versus 53% refusals on trials > 0.2s).
On a subset of trials where infants hesitated, they obtained additional information by touching slopes (48% trials). Duration of touches ranged from 0.5s to 34.3s but most were relatively brief (M = 4.3s). Most touches (77%) were close simulations of walking and were maximally informative. Babies straddled the brink with their feet and rocked back and forth over their ankles or they made small stepping and swaying movements with their feet on the edge of the slope. The remainder of touches were pats and probes with the hands. All touches involved active movement and were accompanied by looking. After touching, infants were more likely to refuse to walk than on trials where they did not touch (61% of touch trials versus 21% of no-touch trials).

Like latency and touching, shifts in position increased on increasingly risky slopes. Overall, number of shifts per trial ranged from 0 to 10. The fact that shifts in position exceeded 1.0 at each slope increment steeper than slope boundary (see Fig. 4.3d) suggests that babies explored various positions rather than selecting a predetermined descent strategy from their repertoire. In contrast to other forms of exploratory activity, shifts in position were nearly always followed by refusals to walk (93% of trials), suggesting that infants had already decided that slopes were too steep to walk safely before they began exploring alternative options.

The systematic relationship between exploratory activity and perceptual judgments is even more evident in the behaviors of individual infants. Figure 4.4 shows four groups of babies, grouped according to the slope increment where their go ratios dropped consistently ≤ .50. Reading along the top row of graphs in Fig. 4.4, the 17 infants in group A displayed the most conservative and accurate perceptual judgments, most closely geared to the probability of successful walking. Their go ratios dropped to ≤ .50 at slightly risky slopes (+5° steeper than slope boundary). The two babies in group B refused to walk at intermediate slopes (+13° steeper than slope boundary). The eight infants in group C continued to walk until approaching impossibly risky slopes (+18° steeper than slope boundary). The four infants in group D attempted to walk down every slope indiscriminately. The next three rows of graphs show three measures of exploratory activity for each go ratio group. Reading down columns, we see that children hesitated, touched, and shifted positions at approximately the same slopes where their go ratios decreased. That is, exploratory behavior on the starting platform predicted infants’ success at safely navigating slopes. Group A hesitated, touched, and tested alternative descent methods at slope boundary or slightly steeper. Group B began to explore on the intermediate range of slopes. Group C did not explore until challenged with impossibly steep slopes. Finally, the hapless infants in group D never hesitated or tested alternative positions and they touched slopes indiscriminately.

**Variety of Means for Descent.** Recognizing that some slopes were risky for upright locomotion was only part of the story. Infants also recognized that on risky slopes, various sliding positions could serve as a means for descent. Of 184 trials scored as refusals to walk, on 83% they found an alternative method to achieve their goal: sliding in a sitting position (39%), backing down feetfirst (32%), crawling on hands and knees (9%), and sliding headfirst prone (3%). Although any single sliding strategy would have
been sufficient to descend risky slopes, many infants used multiple methods. One infant used three sliding positions, 10 toddlers used two strategies, and 14 babies used only one method (two of the reckless infants in group D never refused to walk on risky slopes).

Prior experience using various descent methods in other contexts was not related to infants' methods of descent in the laborotory slope task. Nearly every child had descended from furniture by scooting backward first. Slightly more than half had descended stairs in a backing or sitting position, and one third had gone down a toddler slide independently. However, knowing a strategy for getting down did not mean that children knew when to use the strategy. Use of the various descent methods on laboratory slopes was spread randomly across infants with and without prior experience. Similarly, children with previous slide and stair experience were distributed evenly across the four go ratio groups. Moreover, having experienced a serious fall prior to the test session was not related to infants' descent strategies or perceptual judgments. Apparently, infants treated the slope task as novel and they used means–ends exploration (shifting positions on the starting platform) to discover various means for descent online.

Summary: How Toddlers Cope With Slopes. In sum, results of this study showed that young walking infants display impressive flexibility in coping with locomotion over slopes. Rather than a set of prespecified responses acquired prior to testing on slopes, infants’ behaviors have all the hallmarks of adaptive action—online prospective control of movements, a tight fit between their own physical propensities and the properties of the environment, and variety of means for solving a novel motor problem. They guide locomotion prospectively by spontaneously generating looking, swaying, and touching movements to differentiate safe from risky slopes. They judge the potential consequences of maintaining their current upright posture based on the relationship between surface slant and their individual physiques and level of walking skill. On risky slopes, they explore and use a variety of sliding positions to navigate descent.

Moreover, this experiment illustrates that the study of flexibility in infant skill acquisition is eminently feasible. A modified psychophysical procedure yields detailed data about the adaptiveness of individual infants’ responses. Careful observation of infants’ exploratory behaviors sheds light on the informational basis for their perceptual judgments and the online decision-making process underlying prospective control of locomotion. An age-matched control design provides a way to assess the effects of various developmental factors on individual differences in responding. The next study examined the role of developmental changes more closely by experimentally inducing changes in infants’ body dimensions and walking skill.

4. Flexibility and Specificity

Coping With Changes in Body Dimensions and Walking Skill

Infants’ growth during the first 2 years of life represents nearly unparalleled physical changes (the fetal and pubertal periods and women’s growth during pregnancy are also dramatic examples of physical changes). Babies undergo sudden, surprisingly large growth spurts, showing no change in body dimensions for days or weeks on end, then spurting forward literally overnight (Lampl, 1983; Lampl et al., 1992). Moreover, babies don’t just get bigger. Their body mass redistributes from the top-heavy dimensions characteristic of newborns to the more slender and cylindrical proportions characteristic of preschoolers, and their ratio of muscle mass to fat increases. It is as if infants’ bodies are growing to fit their comparatively large heads.

Changing body dimensions are important because they affect the physical constraints on keeping balance. More babyish top-heavy dimensions, for example, make the body less stable during stance and locomotion. Destabilizing torques build up faster as the body sways back and forth and more muscle torque is required to keep the body within its region of permissible sway. More mature cylindrical dimensions make the body more stable. With a lower center of mass, less muscle strength is required to move the body in the same angular distance. Thus, the redistribution of body mass and the rapid replacement of fat tissue with muscle throughout infancy should augment possibilities for action.

Since the 1930s, researchers have assumed that rapid growth in infancy must affect motor skill acquisition (e.g., Shirley, 1931; Thelen, 1984). For example, several studies found modest correlations between children’s body proportions and when they began crawling and walking. More maturely proportioned babies with higher muscle-to-fat ratios crawled and walked sooner than more top-heavy, chubbier infants (Adolph, 1997; Adolph, Vereijken, & Denny, 1998; Garn, 1966; Shirley, 1931). However, there is little direct evidence that changes in body dimensions affect how well children crawl or walk, and there is little work examining how children might cope with novel changes in their own bodies. The following study examined whether infants display flexible adaptation to functional changes in body proportions and if so, how they managed it (Adolph & Avolio, 2000).

Walking With Weights. Twenty 14-month-old walking infants (10 girls, 10 boys) participated. All babies could walk at least 12 feet independently; walking experience ranged from 3 to 107 days ($M = 62.55$ days). Three infants had prior experience on playground slides, eight had experience walking down wheelchair ramps or sloping lawns, and nine had experience descending stairs.
To examine how infants recalibrate actions to account for rapid, developmental changes in body dimensions, we experimentally manipulated babies’ dimensions via lead-weight shoulderpacks. Then, to exacerbate the problem of keeping balance, we challenged babies to walk down slopes. Infants were fitted into an adjustable, padded vest with removable velcro shoulderpacks (see Fig. 4.5). On some trials, the shoulderpacks were filled with feather-weight polyfill (120g) and on other trials they were filled with lead weights (25% of each infant’s body weight). Based on pilot data, 25% of body weight was the maximum infants could tolerate before their knees collapsed. The feather weights only increased the girth of infants’ chest dimensions. In contrast, the lead weights added to infants’ overall mass and raised their center of mass from an average of 58.7% of standing height to 65% of standing height or by an average of 3.11 cm. The effect of this manipulation was to reduce the angular distance that infants could sway forward and backward before losing balance. When babies stand perfectly upright, the torque acting on their bodies is 0. When infants sway back and forth with their bodies at an angle, the torque acting on their bodies is represented by a sine function. While wearing the lead weights, the sine of the angle of permissible sway was reduced by an average of 25% when infants swayed around their ankles and by 35% when they swayed around their hips.

We tested infants on an adjustable sloping walkway (0’ to 88’). As in earlier studies, parents stood at the end of the landing platform and encouraged their infants to descend. An experimenter followed alongside infants to ensure their safety if they began to fall. The appropriate shoulderpacks were attached at the start of each trial so that infants would be forced to decide online whether slopes were safe or risky for walking relative to their current body dimensions. We reasoned that the same absolute degree of slope could be safe in the feather-weight condition but risky in the lead-weight condition.

We designed a psychophysical double staircase procedure to test each infant in both feather-weight and lead-weight conditions (Adolph & A voxel, 2000). The experimenter ran two independent staircase protocols in tandem so that the weighting conditions were interleaved quasi-randomly. Babies began with an easy 4’ baseline slope. After each successful trial (walked safely), the experimenter increased slope by 8’. After a failure (tried to walk but fell) or refusal to walk (slid down or avoided descent), the experimenter presented infants with a shallow baseline slope of 4’ to provide them with an easy success and to maintain their motivation to continue. Then, the experimenter removed the shoulderpacks for the current condition, attached the shoulderpacks for the other condition, and switched from the current staircase protocol to the other protocol. Upon reentering a staircase protocol, the experimenter presented infants with a slope 4’ shallower than the last unsuccessful trial for that condition. This process continued for each protocol until the experimenter identified a slope boundary to a 75% criterion—the steepest slope that infants walked down successfully at least three out of four times and less than three out of four times at the next 4’ and 8’ increments. On average, each infant had 75 slope trials total.

**Slope Boundaries.** As predicted, experimental manipulation of infants’ body proportions had immediate effects on their walking skill. The lead weights hampered their ability to walk down slopes. Walking boundaries ranged from 4’ to 24’ in the feather-weight condition and from 0’ to 16’ in the lead-weight condition. Overall, infants had steeper walking boundaries in the feather-weight condition (M = 12.0’) than the lead-weight condition (M = 7.6’). Three babies had boundaries 12’ steeper in the feather-weight condition, 13 infants had boundaries 4’ steeper, and four babies had identical boundaries in both conditions. Infants’ walking experience and footprint measures of their walking skill on flat ground predicted their walking boundaries on slopes in both conditions, attesting to the validity of the estimates derived from the staircase procedure. More experienced infants with mature gait patterns on flat ground had steeper walking boundaries on slopes.

**Flexible Online Recalibration.** Could infants adapt to their altered bodies and skills? The strongest evidence for flexible, online recalibration...
would be a difference in infants’ go ratios based on weighting condition at the same absolute degree of slope. Because the lead weights hampered infants’ ability to walk down slopes, the same absolute degree of slope could be safe in the feather-weight condition but risky in the lead. For example, the degree of slant at infants’ feather-weight boundary was safer (higher probability of success) while walking with feather-weight shoulderpacks than with lead. Indeed, comparisons between infants’ go ratios in the feather-weight and lead-weight conditions at feather-weight and lead-weight walking boundaries showed significant effects for condition and for slope. That is, infants were more likely to walk down the same absolute degree of slope while loaded with feather weights than with lead and they were more likely to walk down their shallower lead-weight slope boundary than their steeper one (see Fig. 4.6). Given the constant switching between weighting conditions from trial to trial, these results could only be obtained if infants recalibrated their judgments to their current body dimensions and degree of slope online, based on information they obtained at the start of the trial.

Despite strong evidence that infants’ decisions were affected by weighting condition, recalibration to relative degree of risk was not complete. Perfect recalibration would be indicated if feather- and lead-weight go ratio curves were superimposed after normalizing each curve to its respective slope boundary. If infants responded more cautiously or more recklessly while wearing lead weights, then the lead-weight go ratio curve would be displaced respectively to the left or the right of the feather-weight curve. Figure 4.7a shows infants’ go ratio curves normalized to the appropriate slope boundary. Although both go ratio curves decreased with increase in relative degree in risk, the discrepancy between weighting conditions at slightly risky slopes (+4° and +10°) indicates more reckless errors while wearing lead weights.

**Exploratory Movements.** As in the earlier studies, duration and type of exploratory movements predicted the functional outcome of each trial. If infants hesitated on the starting platform, even for a few brief moments, they were more likely to refuse to walk (66% and 62% of trials in feather- and lead-weight conditions, respectively) than if they did not hesitate on the starting platform (11% and 6% of trials in feather- and lead-weight conditions, respectively). During the time that they hesitated, infants peered over the brink, stepped and swayed on the starting platform, touched slopes, tested alternative sliding positions, and occasionally appealed to their parents or the experimenter for help. In both weighting conditions, infants touched slopes primarily with their feet (94% of trials in both feather- and lead-weights), by rocking back and forth over the ankles at the brink of the slope. They were more likely to refuse to walk after touching slopes (70% and 78% of trials in feather- and lead-weight conditions, respectively) than if they did not explore the surface by touching (30% and 27% of trials).

Differences in infants’ exploratory movements due to weighting condition may explain the discrepancy between go ratio curves. On the same slightly risky slopes where they erred more frequently in the lead-weight condition, babies explored less, not more, while wearing their lead-weight shoulderpacks (see Figs. 4.7b and 4.7c). Latency and touching only diverged at the +4° and +10° slope increments where go ratios diverged—at precisely those increments near slope boundary where extended exploratory movements should prove most useful for distinguishing safe from risky slopes. The differences in exploratory movements between the two weighting conditions suggests that infants were sensitive to their altered body dimensions. However, maintaining upright balance while wearing the lead weights may have interfered with infants’ ability to execute exploratory looking, touching, rocking, and swaying movements.

**Variety of Means for Descent.** Just as the lead weights may have restricted infants’ exploratory movements, the heavy shoulderpacks may have hampered infants from adjusting their gait to walk down slopes. On safe, but increasingly difficult slopes preceding the slope boundary, infants showed more modifications in their walking gait in the feather-weight than lead-weight condition (see Figs. 4.7d and 4.7e). In the feather-
weight shoulder packs, they increased step number and step time to walk down steeper slopes (i.e., smaller, slower steps), but in the lead-weight condition, these measures yielded flatter curves.

The problem of coping with altered body proportions affected only decisions about whether and how to walk, not selection of alternative methods of locomotion. In both feather- and lead-weight conditions, infants displayed a flexible variety of means for descending risky slopes. They rarely avoided descent (17% and 19% of refusal trials in feather- and lead-weight conditions, respectively). Instead they slid down backward feet-first (31% and 29%), sitting on their bottoms (34% and 33%), crawling (10% and 11%), sliding headfirst prone (1% in both conditions), and walking while holding the nets for support (5% and 4%). Prior experience with descent in other contexts was not related to infants’ methods of descent in the slope task. There were no differences in total number of descent methods or prevalence of any particular method between children with prior experience descending playground slides or stairs and babies with no prior experience. Apparently, infants maintained a high variety of means for descent by drawing on previous methods already in their repertoires and discovering new methods during the course of the session.

Summary: How Toddlers Cope With Changes in Body Dimensions and Skill. Toddlers do flexibly adapt locomotion to experimentally induced changes in body dimensions and walking skill. However, when their body proportions are unpredictable from trial to trial, recalibration to relative degree of risk is not complete. Infants were more likely to refuse to walk at the same absolute degree of slant while wearing the lead weights than the feather, indicating that go ratios did not depend solely on degree of slope. However, infants were also more likely to overestimate their ability on slightly risky slopes in the lead-weight condition compared with the feather. The differences between weighting conditions were not an artifact due to variability in infants’ behavior or to fatigue. A control experiment, where two “dummy” feather-weight conditions were interleaved in an identical double staircase procedure showed no differences between dummy conditions for any outcome measures at any degree of slope (Adolph & Avolio, 2000).

Accurate online decisions require updated perceptual information about the current state of affairs. The relevant information can be obtained from a rich variety of exploratory movements—looking, swaying, touching, testing different positions, etc. As in the earlier studies with this age group, exploration tended to mirror perceptual judgments. When infants obtained the requisite information via looking and touching, their judgments were more accurate. When they did not explore slopes, they tended to err. The lead-weight loads in the current study caused infants to keep
their bodies in a stiff upright posture, thereby hampering them from performing their usual range of exploratory movements and gait modifications. In contrast, maintaining a wide variety of means was unaffected by physical constraints. After deciding not to walk, infants generated a rich repertoire of alternative descent methods.

4. FLEXIBILITY AND SPECIFICITY

FLEXIBILITY AND LOCOMOTOR EXPERIENCE: WHEN LEARNING DOES AND DOES NOT TRANSFER

The question of how experience in one context facilitates performance in a different context is central to the concept of transfer, but learning is not necessarily required for the concept of flexibility. In principle, motor skills could be adaptive across a wide variety of novel contexts without the need for practice or experience. In this section, we present evidence that flexibility in infant locomotor skill acquisition does, in fact, involve learning. Drawing on studies of infants' behavior at the edge of slopes and cliffs, we show that the duration of motor experience is the key to adaptive responding. Flexibility is not apparent at the start of mobility and it does not depend on pure physical maturation or other age-related changes independent of experience.

In addition, we describe cases where learning does and does not transfer. The transfer data support our claim that learning does not entail a fixed repertoire of responses, a set of stimulus–response bonds, knowledge about a body schema or of one's own abilities, or even common sense knowledge about properties of the ground and their consequences for locomotion. Rather, learning entails acquiring the tools for online decision making—prospective control of movements based on relational information about current capabilities vis-à-vis the properties of the environment, and a variety of means to achieve the desired end state.

Transfer From Flat Ground to Slopes but Not From Crawling to Walking

Longitudinal Design. A longitudinal study was designed to separate the effects of age and locomotor experience in infants' ability to cope with safe and risky slopes (Adolph, 1997). We observed changes in flexibility over the entire course of locomotor skill acquisition, from infants' first crawling steps, over the transition from expert crawler to novice walker, and then for several weeks after walking onset. The study controlled for the duration of infants' everyday crawling and walking experience and allowed age to vary freely within test sessions. Of special interest was what happened over the transition from crawling to walking, when the same experienced crawlers faced the same slopes as novice walkers.

Fifteen infants (seven girls, eight boys) in an experimental group were tested every 3 weeks, from their first week of crawling until several weeks after they began walking. Weekly phone calls, home visits, and lab visits ensured that each child's crawling and walking onsets were identified precisely. Most babies were observed for 22 or more weeks of crawling, although duration of crawling experience was variable (one infant crawled for only 1 week and another crawled for 37 weeks). Most babies were observed for 13 or more weeks of walking. Fourteen additional infants (seven girls, seven boys) in a control group were tested only three times at matched sessions (first week of crawling, tenth week of crawling, and first week of walking) to control for effects of repeated testing in the laboratory. Across both groups, there was a wide range in the age at which infants began crawling (4.8 to 9.6 months) and walking (9.3 to 14.9 months). Thus, age varied widely (range ~ 5 months) at each test session.

Procedure. Infants were tested using Adolph's (1995) psychophysical staircase procedure. Crawlers began each trial in a prone position on the starting platform and walkers began in an upright position. Parents waited at the bottom of the landing platform and encouraged their babies to descend. An experimenter followed alongside infants to ensure their safety if they began to fall. After successful trials, the experimenter increased slant by 6°, and after consecutive failures or refusals, she decreased slant by 4°. Easy 4° baseline trials were interspersed with staircase trials to maintain infants' motivation. The process continued until converging on a slope boundary to a 67% criterion. After identifying slope boundary, the experimenter presented infants with multiple probe trials at slightly risky slopes (6° steeper than boundary), intermediate slopes (12° steeper), impossibly risky slopes (18° steeper), and the steepest 36° slope. Significant correlations at each test session between infants' crawling and walking skill on flat ground and their slope boundaries attested to the validity of the estimates derived from the staircase procedure.

As in the earlier studies, a go ratio indexed the adaptiveness of infants' responses. Perfectly adaptive responses would be indicated by matching the probability of going to the conditional probability of success (i.e., high go ratios on safe slopes and low go ratios on risky ones). Conversely, high go ratios on risky slopes constitute serious errors and indicate lack of prospective control.

Prospective Control Transfers From Everyday Experience. The longitudinal data from this study provide strong evidence that flexible, prospective control depends primarily on everyday locomotor experience, not age. Of course, age and locomotor experience are normally intercorrelated (older children tend to have more experience). However, in the current study
where duration of locomotor experience was held constant, there was no effect for infants’ age at any test sessions. That is, older children fared no better than younger ones when matched for duration of crawling or walking experience. At infants’ final week of crawling, when both age and experience varied freely, experience was a stronger predictor of adaptive responding than age. Moreover, experience independently explained variance above and beyond that explained by age alone, but age did not explain additional variance after experience was partialed out.

Figure 4.8 shows the primary index of adaptive responding and learning: The solid curves represent changes in experimental-group infants’ go ratios (i.e., errors) on risky slopes across the weeks of testing—when crawlers tried to crawl and had to be rescued by the experimenter to prevent injury, and when walkers tried to walk and fell over the brink into the experimenter’s arms. Most notably, the pattern of results indicates that the adaptiveness of infants’ responses was related to the duration of their everyday crawling and walking experience. In their first week of crawling, infants plunged headlong down impossibly steep slopes on trial after trial (average go ratios were .68). Over weeks of crawling, go ratios decreased steadily until by their 22nd week of crawling, infants’ judgments reflected nearly perfectly accurate prospective control of locomotion (average go ratios were .11). Similarly, in their first week of walking, infants walked over the brink of impossibly steep slopes (average go ratios were .65). Over weeks of walking, go ratios decreased again. By their 13th week of walking, average go ratios were .24.

A second noteworthy point from the figure is that learning takes a surprisingly long time. Infants required 10 or more weeks of experience before errors on risky slopes decreased below 50% and 20 or more weeks before errors decreased to approximately 10%. Such slow learning curves represent a massive amount of everyday locomotor experience. In fact, preliminary data from an ongoing home diary study (Chan, Lu, Marin, & Adolph, 1999) points to a staggering amount of varied experiences in infants’ first months of crawling and walking. New crawlers spend approximately 40% of their waking day on the floor, traverse 5 to 13 different surfaces per day, and log 50 to 350 feet per hour. New walkers spend over 50% of their waking day on the floor and take 500 to 1500 walking steps per hour. These preliminary data suggest that infants may take thousands of crawling or walking steps each day and hundreds of thousands of steps across days before they show adaptive responses in a novel task such as descending risky slopes.

In addition, Fig. 4.8 indicates that learning transferred from everyday locomotor experience on safe, flat ground to coping with the novel task of descending risky slopes. No infants in this study had experience on slopes outside the laboratory. Thus, the critical comparison is between the infants in the experimental group (solid symbols) who experienced more than a dozen test sessions and hundreds of trials on slopes and the infants in the control group (open symbols) who were tested only three times on laboratory slopes. There were no differences between experimental and control groups at any of the matched session times. Learning depended only on the duration of infants’ everyday locomotor experience traveling over safe, flat ground at home, not on specific experiences coping with slopes.

Similarly, learning did not depend on specific experiences falling from heights in home accidents or falling down slopes in the laboratory. One child fell down a flight of stairs in a mechanical baby walker and was treated for serious contusions. Another broke his arm in a home accident. Despite these negative experiences in their first weeks of crawling, both babies dragged their bruised bodies over the edge of impossibly steep slopes similar to their inexperienced peers. Likewise, there was no evidence that infants learned to avoid steep hills from falling down laboratory slopes. After falling on one trial, infants were most likely to attempt the same crawling or walking response on the same impossibly steep hill on the very next trial (80% of consecutive trials). When infants slid down or avoided going, they refused outright after a successful trial on a shallower slope (93% of refusals).
Relational Judgments Transfer Over Changes in Body Dimensions and Locomotor Skill. Transfer of experience-driven flexibility from flat ground to slopes was all the more impressive because the definition of safe and risky slopes changed from session to session for each infant. The procedure of normalizing safe and risky slopes to each infant’s current slope boundary ensured that babies must take into account the relationship between their current capabilities and the properties of the ground surface. In fact, infants’ bodies and skills changed dramatically from session to session. For example, average height increased by more than 12 cm across test sessions, weight by nearly 3 kg, and Ponderal Index (overall chubbiness) decreased by 17%. As infants’ bodies got larger and more maturely proportioned, their crawling and walking skill improved. On flat ground, average crawling velocity increased more than five-fold across test sessions, and average walking step length increased by 60%. On slopes, boundaries changed as infants improved at belly crawling, mastered crawling on hands and knees, and became more proficient walkers (see Fig. 4.9). Thus, the learning curves in Fig. 4.8 indicate that infants learned to make flexible, adaptive decisions despite weekly changes in their bodies and skills. A safe hill one week could be risky the next, and vice versa, depending on infants’ current method of locomotion and current level of locomotor skill.

Variety of Means Transfers From Crawling to Walking. Just as infants learned to control locomotion prospectively and to base their judgments on the relationship between their own abilities and the ground surface, they slowly acquired a variety of means for coping with descent. On average, avoidance appeared first at infants’ 4th week of crawling, sliding headfirst prone like Superman in their 13th week of crawling, sliding in a sitting position in their 16th week, and sliding backward feetfirst in their 19th week. Nearly every infant demonstrated multiple descent methods for going down slopes. As new options entered their repertoires, infants decreased use of the avoidance response (from 100% to 1% of refusal trials over weeks of crawling) and increased use of the various sliding positions. Most infants maintained all of their newly acquiring sliding positions as viable means of descent within and across crawling sessions. As refusals increased over weeks of walking, infants again used the various sliding positions that they had discovered during crawling. As in crawling, variety of means was maintained within and across walking sessions.

No Transfer From Crawling to Walking. The impressive transfer of prospective, relational control evident over weeks of crawling and walking was matched by equally impressive failure to transfer between crawling and walking. Figure 4.8 shows two parallel learning curves. Apparently, there was no savings from weeks of crawling. Go ratios on risky slopes were just as high in infants’ first week of walking as they were in babies’ first week of crawling, and learning was no faster the second time around.

In fact, infants’ learning was so posture specific that they showed no transfer even from trial to trial. At the end of each walking session, babies were given six back-to-back trials at the steepest 36° slope: two trials in their new upright walking posture, then two trials in their old, familiar crawling posture, then two trials again in their unfamiliar walking posture. As shown in the left panel of Fig. 4.10, infants rarely erred at 36° in their last week of crawling. Similarly, when new walkers were tested in their old familiar crawling posture, they immediately slid down or avoided going. However, when new walkers were tested in their unfamiliar upright posture, they frequently attempted to walk down the same risky 36° slope and fell, requiring rescue by an experimenter.

Summary: Transfer From Flat Ground to Slopes but Not From Crawling to Walking. The longitudinal study of infants’ locomotion over slopes shows that the three hallmarks of adaptive action are learned. Transfer of learning is both remarkably general and surprisingly specific. Adaptive action transfers from everyday crawling and walking experience on flat ground to the novel slope task and across changes in body dimensions and locomotor skill. However, learning does not transfer across developmental changes in posture. Infants acquire prospective, relational, varied control of action over weeks of crawling and again over weeks of walking.

How do we account for both the flexibility and specificity of learning in infant motor skill acquisition? Acquiring a body image or a static concept of their own bodies and skills would have been useless because these aspects of self were changeable within each method of locomotion. Recip-
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for crawling and walking (0% probability of success), perceptually, slopes and cliffs are very different. A slope has a continuous visible surface texture and a cliff has an abrupt discontinuity in visual texture gradients. A slope has a surface that can be probed and felt with the hands and feet, a cliff does not. Many properties of a sloping surface have practical consequences for locomotion (degree of slant, size of the vertical drop-off, length of the slope itself, rigidity of the surface, frictional properties, surface relief, etc.), but the relevant properties of a cliff involve only its dimensions. Finally, a steep slope has several alternative options for managing descent (sliding down in backing, sitting, or prone positions) but a large cliff is not navigable by human infants and requires avoidance.

Since Gibson and Walk’s classic studies (Gibson & Walk, 1960; Walk & Gibson, 1961; Walk, Gibson, & Tighe, 1957), most researchers have tested animals’ and babies’ responses to a sheer drop-off on a “visual cliff” rather than a real one. To ensure participants’ safety, the cliff is covered in invisible glass. In the usual arrangement, a narrow starting platform divides a glass table. On the “shallow” side of the divide, a patterned surface is placed directly beneath the glass so that the surface looks continuous. On the “deep” side of the divide, the same patterned surface is placed far below the glass so that the surface looks like a cliff. The animal or baby is coaxed to cross first one side, then the other, using the parent, food, or a toy as a lure. The primary outcome measures are percent of subjects who avoid crossing the deep side versus the shallow side and their latency to begin traversal.

The Role of Experience in Visual Cliff Avoidance. The young of some precocial (already locomotor) species avoid the apparent drop-off on the visual cliff on their first exposure (e.g., Gibson & Walk, 1960; Walk & Gibson, 1961; Walk et al., 1957). Baby chickens and goats, for example, walk or hop over the shallow side of the visual cliff, but adamantly refuse to go over the deep side. When newborn goats are placed directly on the glass covering the deep side, they splay their legs in a defensive reaction and back up toward the starting platform. In fact, Gibson drew inspiration for the design of the first visual cliff from her observation that baby goats will not step off the edge of a stool moments after birth (Gibson, 1991). (Kids are born in pairs and she needed a way to manage one twin while the other was being birthed.)

In contrast, human infants and other altricial species such as kittens and rabbits require a protracted period of crawling experience before they avoid crossing the deep side of the visual cliff (e.g., Campos, Bertenthal, & Kermoian, 1992; Held & Hein, 1963; Richards & Rader, 1983; Walk, 1966). For example, Bertenthal, Campos, and Barrett (1984) demonstrated that the duration of infants’ everyday crawling experience predicts avoidance.
on the visual cliff, independent of crawling onset age or age at testing (see Fig. 4.11). The curves represent avoidance responses in infants with approximately 6 weeks of crawling experience and babies with approximately 2 weeks of crawling experience. Most impressive, comparison of the curves in the middle section of the x-axis shows that at the very same ages at testing (7.5 to 8.5 months), 60% to 70% of experienced crawlers avoided crossing the deep side of the visual cliff but only 30% to 40% of inexperienced babies did likewise. Bertenthal and Campos (1984) argued that the beneficial effects of everyday crawling experience are likely to be asymptotic rather than strictly linear. Thus, we should expect the strongest effects for experience in the first few months after infants begin crawling before avoidance responses reach asymptote.

Although infants must learn to avoid a precipitous drop-off, their learning does not reflect any sort of simple associative pairing between the depth information for a drop-off and the negative consequences of falling. Rather, avoiding the visual cliff reflects the same sort of flexible, adaptive, online decision making that babies displayed in the slope tasks. For example, negative experiences falling from heights are not related to avoidance on the visual cliff (Scarr & Salapatek, 1970; Walk, 1966); inexperienced crawlers are likely to cross the visual cliff regardless of whether they experienced home accidents falling from a steep place in the course of crawling. Similarly, adaptive avoidance responses do not depend on actual experience with the visual cliff. For approximately 15 days after they become locomotor, kittens and bunnies safely cross the deep side of the visual cliff without incident, then they subsequently avoid it (Walk, 1966). More-

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over, like the babies who learned to cope with novel slopes as crawlers but showed no transfer to a new walking posture, adaptive avoidance responses at the edge of a cliff may be specific to the posture in which infants have acquired experience. In a clever within-subject design, Rader, Bau-
sano, and Richards (1980) showed that infants with several weeks of home crawling experience avoided crossing the visual cliff when tested in their experienced crawling posture. However, moments later, the same babies went right over the deep side when supported upright in mechanical baby walkers. The critical experience for promoting visual guidance of locomotion appears to stem from using one’s own powers to maintain balance in a particular body posture while moving over various visually patterned ground surfaces.

Of course, the visual cliff is, in fact, perfectly safe for locomotion, and human infants eventually learn that transparent surfaces can provide support for locomotion. Such learning is problematic for studies involving repeated testing but interesting for examining how infants learn about transparency. When babies are tested longitudinally or given multiple trials in cross-sectional studies, avoidance responses actually attenuate in some experienced crawlers after repeated exposure to the glass surface (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Eppler, Satterwhite, Wendt, & Bruce, 1997). Instead of avoiding, infants display long latencies, all the while peering down into the crevice, then cross using ingenious compromise strategies such as detouring along the wooden edge of the glass platform, attempting to back into the precipice, or crawling midway over the glass then stretching out an arm as though trying to bridge the remaining gap with their extremity. Similarly, Titzer (1995, March) found that infants who had been given several weeks of home experience playing with transparent, plexiglass boxes subsequently crossed the visual cliff after long latencies and a strong push on the glass surface with their hands. Although they are uncomfortable locomoting over a surface while they can see the ground far below their bodies, babies can learn about the substantial properties of a transparent surface for supporting their bodies.

**Sitting and Crawling at the Edge of an Adjustable Gap.** In two recent studies (Adolph, 2000; Adolph, Avolio, Melton, Arnet, & Eppler, 1998), we expanded on our earlier finding of specificity of learning from crawling to walking in infants’ locomotion over slopes and Rader et al.’s (1980) finding of specificity of knowledge from prone to upright postures on the visual cliff. However, rather than testing babies in an experienced crawling posture versus an unfamiliar walking posture, we tested them in an experienced sitting posture versus an unfamiliar crawling posture. And rather than testing babies on slopes or a visual cliff, we tested them at the edge of an actual precipice.

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**FIG. 4.11.** Percent of infants who avoided the visual cliff as a function of age and crawling experience. Figure adapted from Bertenthal, Campos, and Barrett (1984).
We built an adjustable "gaps" apparatus by constructing a stationary, wooden starting platform (106 cm long × 76 cm wide × 86 cm high) and a moveable landing platform (158 cm long × 76 cm wide × 86 cm high). By sliding the landing platform back and forth along a calibrated track, we could create a gap between the two platforms, varying in 2 cm increments from 0 cm to 90 cm. Both platforms were covered in carpet and the floor of the crevice was padded with foam. As in earlier studies, parents stood at the far side of the landing platform and encouraged their babies to cross the gap. An experimenter followed alongside infants to ensure their safety if they began to fall.

The experimental design capitalized on the overlap in timing of two postural milestones: an earlier developing sitting posture and a later developing crawling posture. Nine-month-old infants were tested in a familiar sitting posture where they had a great deal of experience maintaining balance (approximately 3 months), and in a less familiar crawling posture where they were relative novices at maintaining balance (approximately 1.5 months). In both postures, their task was to decide whether they could lean forward over the gap without falling into the crevice (see Fig. 4.12). In the sitting posture, infants sat at the edge of the gap with their legs dangling into the hole. A toy was suspended at the end of a stick to provide an incentive for babies to lean forward and stretch an arm out over the gap. In the crawling posture, babies began in a prone position on the starting platform. A toy was placed on the landing platform to encourage them to lean forward and stretch an arm out over the gap. This task was relatively novel. No infants had prior experience crawling over holes in the floor or sitting at the edge of a precipice without external support to strap them in.

Adolph's (1995) psychophysical staircase procedure was used to identify the largest gap each infant could span in each posture—their sitting and crawling gap boundaries. Then the experimenter presented infants with multiple trials on safe and risky gaps (6 cm smaller than gap boundary, 6 cm, 12 cm, and 18 cm larger than gap boundary, and trials at the largest 90 cm gap). The latter 90 cm gap was the same dimensions as the traditional visual cliff, minus the safety glass. We reasoned that if experience precipitates learning something general about ground surfaces, then infants' actions at the edge of an impossibly large gap should be the same regardless of the posture in which they are tested. If, on the other hand, experience facilitates a more specific form of learning how to maintain balance within a specific postural system across a wide variety of situations, then babies should demonstrate more adaptive, prospective, and relational control of action in their more experienced sitting posture.

In two separate experiments, infants exhibited highly adaptive responses in their experienced sitting posture and surprisingly maladaptive responses in their less familiar crawling posture (see Fig. 4.13). In the sitting posture, they consistently matched the probability of avoiding to the probability of falling. That is, they leaned forward to retrieve the toy on safe gaps where the goal was within reach, and avoided leaning forward on increasingly risky gaps where they were likely to fall. In contrast, in the crawling posture, they crawled into impossibly large gaps on trial after trial, requiring rescue by the experimenter. At every risky gap increment, infants made more errors in the crawling posture than the sitting posture. In fact, several infants in both experiments attempted the largest 90 cm gap in the crawling posture, which was tantamount to crawling into thin air. All babies avoided the 90 cm gap in the sitting posture. As in earlier studies, there was no effect for condition order and no evidence of within-session learning from falling on previous trials. Also, as in earlier studies, there was no evidence that prior experiences falling over drop-offs (e.g., edge of bed, changing table, stairs) affected behavior in the novel laboratory task.

Summary: Transfer From Solid Ground to Cliffs but Not From Sitting to Crawling. Like the crawling and walking infants on slopes, findings from sitting and crawling babies on cliffs and gaps provide further evidence that flexibility, like the old concept of transfer, requires learning. Over weeks of everyday experience maintaining balance in particular body postures on safe, solid ground, infants acquire the wherewithal to make adaptive decisions for maintaining balance at the edge of a novel, potentially risky precipice. Experience facilitates flexibility when faced with novel contexts in a familiar body posture, but leads to specificity when faced
not acquire static concepts of their own abilities. Infants recalibrated to both naturally occurring changes and experimentally induced changes in their body dimensions and locomotor skill. They do not learn fixed associations between specific environmental properties and specific motor responses. Babies adapted their responses to the current status of the actor–environment fit and they displayed a wide variety of alternative locomotor strategies from trial to trial. Their responses are not mediated by acquisition of a fear of heights or fear of falling. Babies rarely displayed negative emotions of any sort in any of the experimental tasks (Adolph & Eppler, 1999; Sorce, Emde, Campos, & Klinnert, 1985; Stergiou, Adolph, Alibali, Avolio, & Cenedella, 1997), and it is unlikely that fear would wax and wane with changes in body postures. Finally, there is no evidence of one-trial learning or of learning from falling within the testing session.

Posture-Specific Learning About Balance Control: The Region of Permissible Sway

An explanation that can account for both the impressive flexibility and surprising specificity described in this chapter is that infants are learning about balance control. They learn to detect threats to balance and they learn compensatory strategies for when balance is disrupted.

In quiet stance and locomotion, the body is always swaying to and fro in a cyclical process of imminent balance loss and recovery. To prevent themselves from falling over, infants must maintain their bodies within a region of permissible postural sway (Riccio, 1993; Riccio & Stoffregen, 1988). The extent of this region is defined by the available muscle torque relative to destabilizing torque. Babies will lose balance if their bodies move outside their base of support without sufficient muscle strength to pull themselves back into position.

Typically, balance control appears effortless because we keep our bodies well within the region of permissible sway. Balance control is threatened when variations in the ground surface or changes in body propensities increase the ratio of destabilizing torque to muscle torque above tolerable limits. This narrows the region of permissible sway or quickens the body’s movement toward the outer limits of reversibility. A downward slant, for example, narrows the sway region by decreasing the base of support and increasing the vertical distance that the body falls during each step. A weighted vest narrows the sway window and increases destabilizing torque by increasing the body mass above the pivot point. A small drop-off or gap in the surface of support requires infants to place their extremity on the far side of the hole before toppling over. On an impossible large cliff, of course, balance is disrupted because there is no floor at all to support the body. In fact, the size of the sway window fluctuates from step

with a familiar task in a novel body posture. The following section focuses on what infants may learn that promotes both flexibility and specificity of responding.

WHAT INFANTS LEARN THAT PROMOTES BOTH FLEXIBILITY AND SPECIFICITY

What, then, might infants learn? The empirical results belie several traditional, common-sense explanations. Infants do not learn a set of facts about surfaces. Although steep slopes and precipitous drop-offs are dangerous in any posture, infants’ knowledge was posture-specific. They do
to step, with every irregularity in terrain, with every change in the location of the center of mass due to body movements or shifting a load, etc.

Thus, the trick for keeping balance is to continually gauge the region of permissible sway against the available muscle torque for counteracting destabilizing torque. Perceptual information is required to specify the extent of spontaneous swaying motions and the results of compensatory sways to recover balance. Exploratory looking, swaying, and touching movements yield redundant information about the current status of the sway region.

Learning the appropriate exploratory movements to maintain balance might be general with respect to surface properties and body propensities, yet specific with respect to developmental changes in posture because each postural milestone represents a different balance control system (see Fig. 4.14). Each postural milestone has a different set of relevant parameters for gauging the region of permissible sway and keeping the body within tolerable limits. Sitting, crawling, and walking postures, for example, involve different key pivots around which the body rotates (e.g., the hips for sitting, the wrists for crawling, and the ankles for walking). Each posture involves different muscle groups for executing movements and for generating compensatory sway, different vantage points for viewing the ground surface, different frequency and amplitude of optic flow information as the body sways back and forth, different extremities for obtaining haptic information, different correlations between visual, kinesthetic, and vestibular information, and so on. Variations in the ground or in body propensities affect only the settings of the relevant parameters—that is, the size of the sway region. The developmental shift from one postural milestone to another presents a different problem. New postures actually involve new control parameters. Thus, infants may require extensive experience with each postural milestone in development to define the relevant parameters for the new balance control system and to facilitate the online calibration of parameter settings.

Step-to-Step Exploration in the Service of Action

How might infants gauge their current region of permissible sway on a step-to-step basis? Our analyses of infants’ behavior at the edge of potentially risky surfaces indicate a sequential process of exploration in adaptive online decision making (Adolph, 1997; Adolph & Eppler, 1998, 1999). Visual exploration serves as the first strategy for guiding action. Babies take a quick glance at the ground ahead. If the surface appears similar to the ground beneath their bodies, they continue on their current path without pause. If the surface looks discrepant, they stop, engage in more prolonged visual inspection, and sway back and forth or take small steps in place. Prolonged looking and swaying/stepping movements produce changes in the speed and direction of optic flow and concomitant changes in vestibular and kinesthetic information about postural control. If these movements specify safe going, infants plunge ahead. However, if something seems amiss, they may obtain additional information from coordinated looking and touching. Tactile exploration is limited largely to situations where the probability of falling begins to increase. Typically, infants touch with their leading extremity and use movements that produce similar forces to those involved in locomotion (rocking and stepping at the brink of the questionable surface). When tactile probes of the ground surface reveal adequate support for locomotion, babies proceed forward but modify their gait by shortening step length and decreasing step velocity. If touching specifies undue risk, they seek out alternative methods of locomotion or navigate a detour around the problem site. Means–ends exploration in the service of locomotion involves multiple shifts in position and partial attempts at traversal. If infants discover an alternative course of action to achieve their goal, they use it. Otherwise, they stay put and fuss. Avoidance appears to be the solution of last resort and typically produces very frustrated infants.

FIG. 4.14. Schematic illustration of region of permissible sway around key pivot for maintaining balance in sitting, crawling, and walking postures.

NEW ANSWERS TO OLD QUESTIONS: ACQUIRING THE TOOLS FOR ONLINE DECISION MAKING

Understanding Transfer in Motor Skill Acquisition

For nearly a century, research on transfer has concentrated on identifying identical elements in training and performance contexts. Accordingly, traditional experimental paradigms have relied on tasks that involve
learning rote routines, stimulus–response associations, fixed contingencies, reinforcement schedules, and so on. For example, dozens of studies (e.g., Kalninns & Bruner, 1973; Rovee-Collier & Gekoski, 1979) have shown that human infants can be operantly conditioned to maintain an experimental contingency between a particular motor response (e.g., sucking, kicking, head-turning) and a particular reinforcer (e.g., the clarity of a visual display, the movement of an overhead mobile). Babies’ spontaneous mouth, head, or limb movements quickly take on an exploratory function as they begin to discover the built-in contingency (Thelen & Fisher, 1983). As movements become more instrumental in maintaining the contingency, they can also become more spare and efficient (Rovee-Collier & Gekoski, 1979). With appropriate variations in stimulus displays during training, babies can even demonstrate stimulus generalization to novel displays (e.g., Greco, Hayne, & Rovee-Collier, 1990). However, the empirical evidence presented in this chapter indicates that traditional learning paradigms such as operant conditioning are poor analogues of everyday motor skill acquisition. They fail to capture the rich and continually changing constraints on movement on both sides of the actor–environment relationship.

Harlow’s (e.g., Harlow, 1949, 1959) discrimination and oddity problems represented a try at something broader than simple associative learning. His notion of “learning to learn” involved acquiring a rule that spanned multiple problem sets. In the discrimination problems, monkeys were presented with dozens of sets of differently shaped block pairs. A raisin was hidden under one block in the pair for the 10 or so trials that comprised that learning set. After several trials, monkeys learned to track the designated block to retrieve the raisin, but when they were presented with a pair of new shapes in the next problem set, they responded at chance levels. Adult monkeys required dozens of problem sets (and hundreds or thousands of trials) before they abstracted a general rule of “win-stay/lose-shift” that would allow them to solve the next discrimination problem in only one trial: If the first lifted block reveals the raisin, track it; otherwise, track the other shape. In the oddity problems, monkeys had to select the shape that was different from three or more blocks. Here, the general rule was to choose the odd one from among a set. Like monkeys, children of normal intelligence and children with mental retardation can learn to solve discrimination and oddity problems (e.g., Levinson & Reese, 1967; Zeaman & House, 1963).

Harlow called this phenomenon learning to learn because it allowed for online problem solving. However, his experimental paradigm cannot serve as an adequate model of flexibility in motor skill acquisition. No simple rule to a single class of problem will suffice for coping with a varying body, a varying terrain, and step-to-step variations in biomechanical constraints.

4. FLEXIBILITY AND SPECIFICITY

Novelty and Variability Require Flexibility

Theoretically, transfer is an important concept because it highlights our need to understand how behavior is adapted to novel and highly variable contexts. We have argued that novelty and variability characterize the essential nature of everyday motor skill. Even expert, adult performance and highly automatized actions such as walking, talking, and driving require an online decision-making process because the biomechanical constraints on movement are continually changing. We walk through a cluttered environment, over various floor coverings, carrying variable loads. We talk with a mouthful of food, with teeth clenched, while gasping for breath, and through interruptions by our interlocutors. We drive unfamiliar rental cars over varied terrain in changeable weather and traffic conditions. Flexibility is the extent to which we cope adaptively with this sea of novelty. It is marked by prospective, relational control of action, and use of a variety of means to achieve a desired movement outcome.

Flexibility is especially paramount in infancy because motor skill is acquired in the context of developmental change. Babies’ bodies change radically and abruptly. They undergo metamorphoses of postural control as they sit up, crawl on all fours, and finally walk upright. They are exposed to new worlds of opportunities for action as their new bodies and skills expose them to an expanded environment. With so much flux, the content of motor knowledge is unlikely to be limited to facts about environmental features, particular motor responses, static mental representations, or fixed associations between stimuli and responses. In fact, such knowledge would be maladaptive in a system that is continually changing. In the experiments described in this chapter—babies locomoting over slopes, walking with weights, and balancing at the edge of gaps and cliffs—infants showed no evidence that their judgments were based on static forms of knowledge. They do not learn particular solutions for particular motor problems or even more general rules for solving a class of motor problems. Instead, they appear to recalibrate online to the changing relationship between environmental properties and their own physical propensities.

In general, the data suggest that infants acquire the tools for online decision making in controlling posture and locomotion. Acquiring flexibility entails the wherewithal to identify novel motor problems and discover viable solutions online. The essential tools are a fluid repertoire of exploratory movements that allow prospective, relational, and varied control of action. The skilled application of these tools across a variety of environmental contexts grows with increasing experience. Surprisingly, these tools are not carried over the transition to new postural milestones. In sum, infant motor skill acquisition is both far more flexible and far more specific than previously recognized.
ACKNOWLEDGMENT

This research was supported by National Institutes of Child Health and Human Development Grant HD23486 to Karen Adolph.

REFERENCES


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