ACTION AS AN ORGANIZER OF LEARNING AND DEVELOPMENT

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Edited by

John J. Rieser
Vanderbilt University

Jeffrey J. Lockman
Tulane University

Charles A. Nelson
University of Minnesota

Cover design by Kathryn Houghtaling Lacey

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Learning to Learn in the Development of Action

Karen E. Adolph
New York University

FLEXIBILITY IN SKILLED PERFORMANCE

Fluency and flexibility are the hallmarks of skilled performance (MacKay, 1982; Schmidt & Lee, 1999). Fluency is what makes skills efficient, coordinated, and beautiful to observe. It is the ability to execute skills consistently, accurately, and rapidly, the same way over and over, with little regard to the varying constraints of the current situation. It involves automatization, associative learning, and stimulus generalization. To land free-throws in basketball, for example, players try to run off the same movements in the same patterns as they have practiced thousands of times before, ignoring everything except the rim of the hoop and the ball going through it. Chess masters exhibit fluency when they draw on a well-practiced series of moves in response to a familiar strategy they recognize in the opponent. On a more mundane level, most professors are fluent at typing on their computer keyboards, answering familiar questions about their work, and reading research articles in their field.

Flexibility, in contrast, is what makes skills adaptive and truly functional. It is the ability to alter ongoing behaviors in accordance with changes in local conditions, to muster an appropriate response to completely novel instances of a problem. Flexibility is akin to Harlow's (1949) notion of "learning to learn." As Stevenson (1972) put it:

> The ultimate goal in any type of learning cannot be the retention of large amounts of specific information. For the most part, this information will be

forgotten. What can be retained are techniques for acquiring new informa-
tion, learning how to attend to relevant cues and ignore irrelevant cues, how
to apply hypotheses and strategies and relinquish them when they are un-
successful. (p. 307)

Rather than repeating old solutions based on associative learning and
stimulus generalization, flexibility involves discovering new solutions to
novel problems online in response to the demands of the current situa-
tion—the NBA superstars who switch from a layup to a slam dunk while
hanging in mid-air, the elegant chess masters who beat computers with
untried moves, the Iron Chef champions who concoct an entire meal in an
hour using a slimy fish as the main ingredient, and so on. Like fluency,
flexibility is central to expertise at both professional and everyday skill
levels. Flexibility allows backyard jocks to block a jump shot in a pick-up
game of basketball, the scruffy chess players in Washington Square Park
to separate tourists from their money, and everyday cooks to come home
and scrape together a fine meal from remnants in the kitchen without ben-
efit of a recipe.

A recent strike by the Broadway musicians' union highlights the differ-
ence between fluency and flexibility. The producers' stance emphasized
fluency. They proposed using prerecorded music, arguing that digital
"virtual orchestras" provide the same beautiful music reliably (and
cheaply) at each performance. The musicians' stance emphasized flexibil-
ity. They argued that the essence of live theater is the difference between
performances. Because real orchestras can be flexible, performances can
be shaped by the immediate eccentricities of the actors and the audience—
the way an actor's change in timing sends the musicians scrambling in a
new tempo and the unexpected hush of the audience leads the musicians
to find new softness of expression.

Traditionally, researchers have focused more on the acquisition of flu-
ency than on flexibility perhaps because the process of attaining fluency is
easier to understand, model, and simulate. A machine, after all, such as a
chess-playing computer or a mobile robot can capture much of the essence
of fluency. In fact replicability is a primary reason for preferring machines
over human operators. The acquisition of flexibility is more difficult to un-
derstand and model because flexibility requires coping with novelty. It re-
quires creativity and generativity. Flesh-and-blood chess masters can beat a
computer because they can create novel solutions to novel problems. Free-
wheeling robots crash into obstacles that any animal or insect would avoid
because the robots cannot find novel solutions to novel problems.

In this chapter, I focus on the acquisition of flexibility. I begin by pro-
posing a simple, general problem-solving framework for understanding
behavioral flexibility—whether in basketball, chess, cooking, or my own
area of expertise, infant balance control. In the second section of the chap-

ter, I describe the biomechanical problem of keeping balance and explain why balance control requires flexibility. In particular, developmental changes in infants' bodies, skills, and environments, combined with the moment-to-moment flux of everyday movements, create a continual series of novel balance control problems. Using infant balance control as a model system to understand the development of behavioral flexibility, in the third section of the chapter, I report several investigations of infants' responses to novel challenges to balance control that support the utility of the problem-solving framework. In the final section, I report several descriptive studies that begin to constrain theorizing about possible mechanisms for acquiring flexibility in balance control.

PROBLEM-SOLVING FRAMEWORK FOR UNDERSTANDING FLEXIBILITY

My approach to understanding behavioral flexibility is inspired by Harlow and colleagues' (e.g., Harlow, 1949, 1959; Harlow & Kuenne, 1949) studies of "learning to learn" in monkeys and preschool-age children. In the 1940s and 1950s, when most researchers were focused on how animals learn conditioned responses to isolated, single problems, Harlow's group studied how animals learn general strategies and rules for coping efficiently with a class of problems. Monkeys solved discrimination or oddity problems while strapped into a Wisconsin General Test Apparatus. In the discrimination task, monkeys were required to choose the rewarded one of a pair of objects that differed on multiple characteristics and shifted in their left-right positions. After 10 or so repetitions, the experimenter introduced a different pair of objects. The process continued until monkeys could solve new discrimination problems with new pairs of objects after only one trial.

Learning to learn across the class of discrimination problems meant that monkeys had learned to explore both objects and to track the one that covered the raisin or peanut—a sort of win-stay/lose-shift rule. Similarly, in the oddity problems, the experimenter presented the monkeys with three objects: two similar and one different. Learning to learn meant that monkeys could solve new oddity problems with new sets of objects in only one trial; they had learned that the different looking object hid the raisin.

Despite the apparent simplicity of the paradigm, acquisition of flexibility in discrimination and oddity problems was extremely difficult. Adult monkeys required hundreds of pairs of objects—thousands of trials—before they had learned how to learn. Likewise, in the experiments with in-

fant monkeys and preschool-age children, youngsters required thousands of trials to demonstrate flexibility.

In the spirit of Harlow's research endeavors, I propose a general problem-solving framework for understanding behavioral flexibility—whether in discrimination problems or any other type of skill. On the problem-solving framework, the acquisition of flexibility requires learners to do three things: (a) recognize a circumscribed problem space, (b) identify the relevant parameters for operating within the problem space and map their allowable values, and (c) acquire the tools for calibrating or setting the values of the parameters online. For example, in discrimination problems, the problem space is narrowly constricted to new pairs of objects. The relevant parameters are the perceptual qualities of the objects on the WGTA tray. The necessary tools include the sensitivity to visually discriminate the two objects, the exploratory procedure of searching the well beneath one of the objects, and the acquisition of the abstracted win-stay/lose-shift strategy.

The central prediction of this problem-solving framework is that once learners acquire flexibility, they should be able to solve novel problems within the perimeters of the problem space. The corollary prediction is that flexibility should not transfer to problems that reside inside the perimeters of a different problem space. Flexibility in solving discrimination problems means that monkeys could solve endless variations of discrimination problems, but flexibility in the discrimination problem space should not help the monkeys solve oddity problems.

After dozens of studies with human children using variants of discrimination and oddity problem sets (e.g., Stevenson, 1972), the study of learning to learn fizzled. One reason for the loss of interest in studying behavioral flexibility may have been the narrow and artificial nature of the experimental tasks. As a model system, discrimination and oddity problems are elegantly simple and easy to control. However, performance on such simple classes of problems does not map clearly onto the rich potential for flexibility in complex everyday activities such as chess, basketball, cooking, and balance control.

I study balance control in infants as a model system for understanding the development of behavioral flexibility for several reasons. First, balance is perhaps the most important accomplishment in motor skill acquisition. It is the basis of all motor skills involving the head and extremities—moving the head to look and listen, moving the arms to interact with objects, and moving the body for stance and locomotion. Thus, understanding flexibility in the problem space of balance has important implications for motor control. Second, because balance control is implicated in most movements, infants have ample opportunities for learning. Third, in contrast to problem-solving domains where strategies are covert mental

processes, in balance control the variables of interest are overt and observable. Fourth, infants' movements are relatively large, slow, and obvious compared with those of adults. As a result, it is relatively easy to observe changes in their movements. Most important, as described later, the need for flexibility is incessant and paramount in balance control. The everyday environment is variable, unpredictable, and full of novel situations. Movements simply cannot be performed in the same way over and over or we will fall. Instead movements must be continually modified to suit the constraints of the current situation.

KEEPING BALANCE

Requirements of Balance Control

For most people, the problem of keeping balance conjures up images of drunken walkers, tightrope walkers, elderly walkers, and infant walkers—situations when balance control seems especially difficult. In fact, the balance control problem is not limited to precarious situations or special populations. Balance is central to all motor skills. Every movement that defies gravity requires balance to stabilize the body and keep it upright. Without balance, we would be like rag dolls, young infants, or some children afflicted with cerebral palsy; we would crumple downward, unable to lift our head, stretch an arm out to reach for a toy, sit up, stand, or locomote.

Figure 3.1A shows a simple physical model of balance control in upright stance. As represented by the dashed lines in the cartoon, the body is always swaying over its base of support (in this case, the body sways around the ankles). The swaying motions are often most noticeable in precarious situations, but are certainly not limited to them. Sophisticated motion analysis techniques reveal subtle back-and-forth swaying motions of the body even in relatively stationary postures such as sitting and standing upright (e.g., Bertenthal & Bai, 1989; Butterworth & Hicks, 1977; Schmuckler, 1997). The body is in subtle motion fighting gravity even when balance is augmented by supporting the body with external structures such as the backrest of a chair, the edge of the kitchen counter or bathroom sink, someone's shoulder, and so on. The forces acting on the body are never perfectly symmetrical, and muscles are never perfectly quiet. Small asymmetries in forces tip the body in one direction, and compensatory swaying responses tip it back in the reverse direction.

To solve the balance control problem, we must keep our bodies within a cone-shaped region of permissible postural sway (Adolph, 2002; McCollum & Leen, 1989; Riccio, 1993; Riccio & Stoffregen, 1988). The narrow bot-
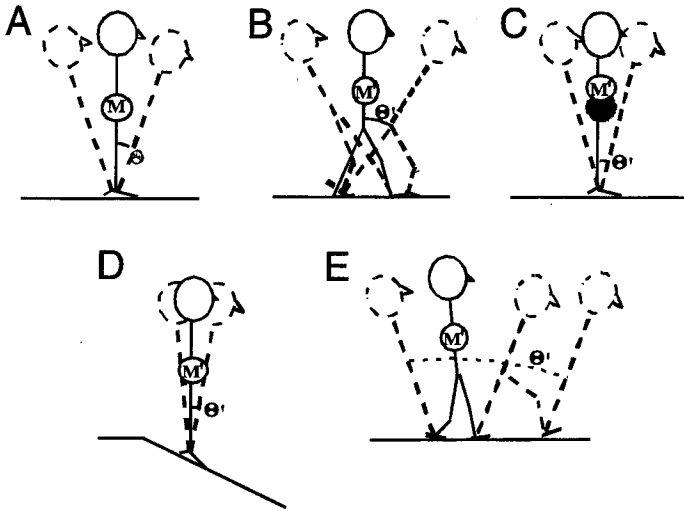
FIG. 3.1.   Physical model of balance control (A) in upright stance with sway around the ankles, (B) with widened base of support by splaying the feet apart, (C) under conditions of altered body dimensions (increased mass and upward displacement of the center of mass), (D) under conditions of variable ground surfaces (sloping ground), and (E) in upright locomotion.

tom or point of the cone is the base of support, and the wide top of the cone circumscribes the body's swaying movements. At any given moment, the size of the sway region depends on the size of the available muscle torque—the current level of strength that the body can muster—relative to the size of the destabilizing torque, the forces acting to pull the body over. Angle θ in the figure represents the angular distance the body can move inside the perimeters of the sway region. If the body moves outside the region of permissible postural sway, we fall.

Changing Constraints on Balance

Biomechanical Constraints.   Balance control requires flexibility because the biomechanical constraints on balance are continually changing. Figure 3.1 shows several sources of change in the size of the sway region. Figure 3.1B shows that widening the base of support increases the size of the sway region by increasing the size of the angular distance the body can move before falling. With the feet close together, as in Fig. 3.1A, the tip of the cone-shaped sway region is small relative to the size of the body, which is acting like a lever arm. Splaying the feet apart widens the base of support. Figure 3.1C shows that functional changes in body dimensions change the size of the sway region. Increased mass and upward or out-

ward displacement of the center of mass (overall weight gain, pregnancy, wearing a backpack, carrying a sack of groceries, etc.) decreases the size of the sway region by decreasing the angular distance the body can move before falling. Figure 3.1D shows that variations in the ground surface change the size of the sway region. For example, sloping ground decreases the permissible angular sway of the body by decreasing the base of support and requiring additional muscle force to maintain the body's vertical orientation. Figure 3.1E shows that in locomotion, the base of support is dynamic, sort of stretching backward and forward in time and space. When running downhill, for example, the torso can momentarily sway far in front of the feet before the legs move back under the body.

In fact, every variation in the body or ground surface changes the size of the sway region in novel ways. Movements change the size of the sway region by changing the inertial forces acting on the body or by recruiting muscles that would otherwise be used for balance. Even drawing a deep breath, lifting the arms, or bending the knees change the size of the sway region by changing the size of destabilizing torque or the effectiveness of the available muscle torque. Thus, keeping balance is a process of continually solving novel problems within the balance control problem space.

Developmental Constraints. Changes due to development also change the size of the sway region. Infants' bodies change dramatically over the first 2 years of life. Neonates' top-heavy, spindly legged bodies morph into toddlers' more chunky, cylindrical bodies. Muscle mass to fat ratios increase, head size to body size ratios decrease, and the center of mass lowers relative to the overall height of the body. Growth spurts are dramatic. Rather than growing taller or heavier along smooth, continuous trajectories, infants' growth is episodic: Sudden bursts of growth (e.g., .5–2.5 cm of height in a single day) are interspersed with weeks of inactive plateaus (Lampl, 1983, 1993; Lampl, Veldhuis, & Johnson, 1992).

At the same time that infants' bodies undergo dramatic change, their skill levels also undergo dramatic change. In part due to the increased biomechanical efficiency of their maturing bodies, infants' movements become more proficient (e.g., Thelen, 1984; Thelen & Fisher, 1982; Thelen, Fisher, & Ridley-Johnson, 1984). For example, speed of crawling, a standard measure of crawling proficiency, more than doubles over the first 10 weeks after crawling onset (Adolph, Vereijken, & Denny, 1998; Freedland & Bertenthal, 1994). Step length, a standard measure of walking proficiency, more than doubles in the first 5 months after walking onset (e.g., Adolph, Vereijken, & Shrout, 2003; Bril & Breniere, 1989).

At the same time that infants' bodies and skill levels undergo dramatic change, their environments expand dramatically. As a by-product of looking more mature physically and demonstrating more proficient skill lev-

els, caregivers begin to introduce infants to new aspects of the everyday surrounds (Garling & Garling, 1988); they may remove the safety gates from the household stairs; provide access to the sandbox, wading pool, or playground apparatus; and encourage infants to explore more broadly and strive toward higher levels of proficiency. Infants, in turn, are better able to take advantage of previously unexplored and untested aspects of the environmental layout.

New Postures in Development. Development changes the sway region in an even more important way. In addition to changing the size of an existing sway region, developmental changes actually create new sway regions. Figure 3.2 shows four postural milestones in infant development. On average, infants sit independently at 6 months, crawl on their hands and knees at 8 months, cruise (walk sideways hanging onto furniture for support) at 10 months, and walk independently at 12 months. The ages and order of acquisition are highly variable (Frankenburg & Dodds, 1967). Some infants cruise before they begin to crawl, sit after they begin to crawl and cruise, or crawl after they begin walking (Adolph et al., 1998; Leo, Chiu, & Adolph, 2000). The normal range in ages spans several months for each milestone. Nonetheless, no infant acquires all four milestones simultaneously. The various postures always appear staggered over several months.

We have argued that each of these postural milestones in development is literally a different balance control system (Adolph, 2002; Adolph & Eppler, 1998, 2002). Each posture involves different relevant parameters with different allowable settings. For example, each posture involves different regions of sway for different key pivots around which the body rotates: the hips for sitting, the wrists for crawling, the shoulders and elbows for cruising, and the ankles for walking. Each posture involves different muscle groups for staying upright and for propelling forward, different vantage points for viewing the ground ahead, different correlations between visual and vestibular input, and so on.

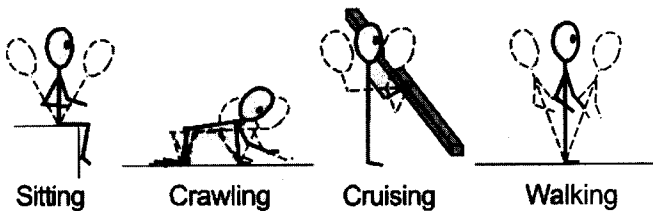Sitting   Crawling   Cruising   Walking

FIG. 3.2.   Four postural milestones in infant development (sitting, crawling on hands and knees, cruising sideways holding furniture for support, and walking). Reprinted from *Ecological Psychology, 10*(3–4), K. E. Adolph & M. A. Eppler, "Development of Visually Guided Locomotion," p. 314. Copyright 1998 by Elsevier. Adapted with permission.

Learning to Learn in the Development of Balance Control. In summary, developmental changes in infancy contribute to variations in the size of a particular sway region. Similarly, at any age, changes due to practice and the manifold changes due to varying local conditions contribute to variations in the size of a particular sway region. All such changes require behavioral flexibility to cope with novel constraints on balance.

In addition to flux in the size of a sway region, development creates new postural control systems—new sway regions—with a whole set of new parameters. We argue that infant balance control provides an especially informative model system for studying developmental contributions to behavioral flexibility because the creation of new postural control systems is a unique product of infant development. On the problem-solving framework, each new posture in development should be considered as a new problem space. With the acquisition of each postural milestone, infants must discover the boundaries of the new problem space, identify the new set of relevant parameters, estimate the allowable range of values for each, and acquire the tools for calibrating the settings of the various parameters.

On our problem-solving account that infants are "learning to learn" about balance, we make several related predictions. First, the adaptiveness of infants' responses should be predicted by the duration of their experience maintaining balance in each posture, not on their chronological age per se. As shown by the individual curves in Fig. 3.3A, within a particular posture, infants should display higher error rates (fall more often) in their first few weeks of experience compared with lower error rates after several weeks of experience. As shown by the vertical arrows in Fig. 3.3A, across postural milestones, infants should make more errors in less familiar postures compared with more experienced ones. Note that we are agnostic about the order in which postural milestones are attained. The learning curves on the figure could appear in any order. Age alone should not predict the adaptiveness of infants' responses because infants may be highly experienced in sitting, for example, at younger ages and inexperienced in walking at older ages.

A second related prediction of the problem-solving account is that learning to learn about balance should be slow, difficult, and fraught with errors. If adult monkeys required thousands of trials to acquire a learning set to solve novel discrimination or oddity problems in Harlow's (1949) simple model system, human infants might require epochs of trials to acquire sufficient flexibility to cope with the exigencies of balance control in everyday life. The problem space for Harlow's studies was extremely narrow and circumscribed (monkeys were engaged in the discrimination or oddity task only in the context of the WGTA apparatus). In contrast, the problem space for balance control is extremely broad. Infants must ac-

A

B

Slope (degrees)   safer ◄————————┼————————► riskier
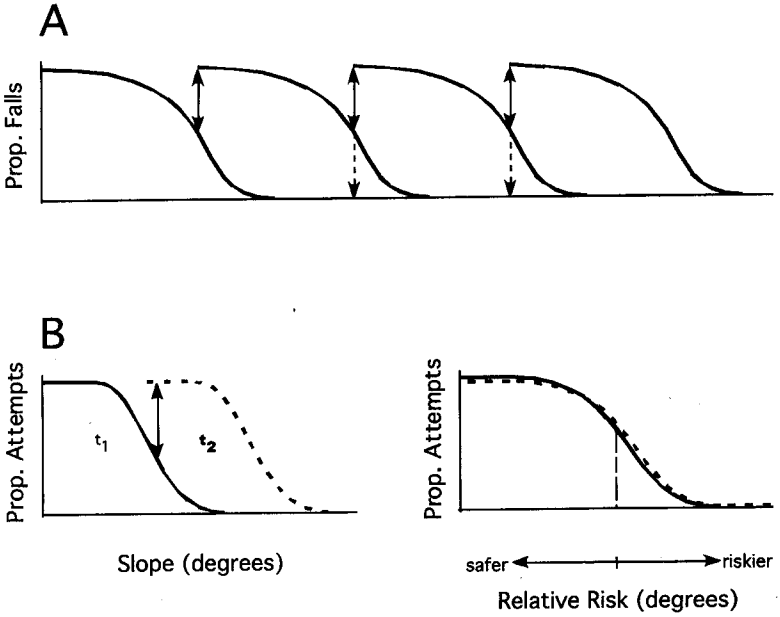
Relative Risk (degrees)

FIG. 3.3.   Learning to learn in the development of balance control. (A) Learning curves for four postural milestones in development. X-axis represents age and experience with each posture. Y-axis represents error rates (falling). Vertical arrows denote differences in error rates due to different durations of experience with each posture with age held constant. (B) Differential responding under different testing conditions (t1 and t2). Curves represent attempts to walk. Left panel shows differential responding plotted against the absolute degree of slope. Right panel shows differential responding plotted against the normalized amount of risk.

tively engage in keeping their bodies in balance during all of their waking hours (even while carried or pushed in a stroller, infants must balance their heads and torsos). Exploratory procedures for searching under the wells in Harlow's studies preexisted in monkeys' repertoires. In contrast, infants must discover and hone many of the exploratory swaying, looking, and touching movements that are required for generating perceptual information about balance control. Most critical, Harlow's monkeys could solve the discrimination and oddity problems by abstracting simple static rules. In contrast, learning to gauge the extent of the current sway region requires infants to abstract dynamic, probabilistic functions.

A third related prediction of the problem-solving framework is that adaptive responding to threats to balance control should be based on the relative amount of risk, rather than on absolute values of the relevant pa-

rameters. Learning to learn would mean that infants should disregard particular facts about themselves and the environment (e.g., 20° slopes are risky for walking or "I'm a poor clumsy walker") because static facts are subject to change from moment to moment and week to week. A particular degree of slope, for example, might be perfectly safe when walking unhindered, but impossibly risky when carrying a load. The same slope might be risky last week when walking proficiency was poor, but perfectly safe this week after dramatic improvements in walking proficiency.

As shown in the left panel of Fig. 3.3B, adaptive responding might require infants to respond differently to the same absolute degree of slope (or any other relevant parameter) under different testing conditions (represented by t1 and t2). The curves in Fig. 3.3B represent attempts to walk. Perfectly adaptive responding would be evidenced by matching the probability of attempting to walk with the conditional probability of success. Instead of learning particular facts about absolute values of experimental variables, learning to learn would require infants to figure out the relative amount of risk in the current situation. As shown in the right panel of Fig. 3.3B, infants' level of learning to learn would be reflected by the equivalence of responding at the same relative amount of risk. The curves on the figure are normalized to the same relative risk level.

A fourth related prediction is that learning should be flexible enough to cope with new problems that change the size of a particular sway region. Thus, experienced infants should respond adaptively across changes in their functional body dimensions and skill level due to naturally occurring changes in growth, strength, coordination, and the like and due to experimentally induced changes such as carrying a load or wearing platform shoes. Similarly, experienced infants should respond adaptively across novel variations in the ground surface. Independent navigation of steep slopes, for example, is a novel task for most infants, as is descending from sharp drop-offs, locomoting over gaps in the ground surface, coping with stairs and bridges, and so on. If infants have truly learned how to learn, under conditions of changing bodies, skills, and ground surfaces, infants should be able to use an acquired repertoire of exploratory movements, compensatory sway responses, locomotor methods, and so on to figure out what to do within a common problem space.

Finally, a fifth related prediction is that learning should be specific to each postural milestone in development. Because learning to learn is limited by the boundaries of the particular problem space, infants should show no evidence of transfer (either positive or negative) across developmental changes in posture. We should see four parallel learning curves as illustrated in Fig. 3.3A.

FLEXIBILITY AND SPECIFICITY IN INFANT BALANCE

In this section, I describe several experiments that support our problem-solving approach to the general problem of behavioral flexibility. Our standard research strategy was to pose infants with novel threats to balance under conditions of changing body dimensions, changing skill levels, and changing ground surfaces. As in the classic visual cliff studies (Gibson & Walk, 1960), where infants were encouraged to cross an apparent drop-off covered with safety glass, in our studies, infants' task was to decide whether a surface was safe or risky for balance and locomotion. Caregivers stood at the far side of the surface offering toys, Cheerios, and praise to provide infants with a compelling reason to cross, but they did not advise infants to be careful and did not tell infants how to cross the surface. If infants attempted to cross, we assumed that they perceived the surface to be safe; if they refused to cross or selected an alternative method of locomotion, we assumed that they perceived the surface to be risky.

In contrast to the visual cliff studies, we did not cover our test surfaces with safety glass. Thus, our test surfaces were not only "visually risky," they actually were risky. In the visual cliff studies, infants could feel the safety glass with their hands or feet. Despite viewing the floor far below, most infants reluctantly crossed after one trial (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Eppler, Satterwhite, Wendt, & Bruce, 1997). As a consequence, individual infants could be tested on only one trial, and they could not be tested longitudinally. Results in visual cliff studies can only be reported in terms of the percentage of infants avoiding or crossing.

By removing the safety glass in our studies, we could test individual infants over dozens of trials in multiple conditions in a single session, and we could observe them longitudinally at tightly spaced intervals over several months. In fact, we could collect enough trials for individual infants to use psychophysical procedures so as to plot crude response curves for each baby in each condition.

We capitalized on the fact that infants do not acquire all postural milestones simultaneously so as to compare their responses in more experienced postures versus less familiar ones. We assessed the adaptiveness of their responding by equating the relative amount of risk over changes in the test conditions. To ensure their safety, a highly trained experimenter followed alongside infants and caught them if they began to fall. Because the sensation of falling downward is highly salient, infants tended to display their most accurate judgments, and the need for adaptive responses was paramount.

Sitting and Crawling Over Gaps

Infants' response to the visual cliff has captivated researchers for nearly half a century. Why do some babies blithely crawl over the safety glass while others remain steadfast on the starting platform? The original explanation for avoiding the drop-off was that infants had acquired depth perception (Gibson & Walk, 1960). However, depth perception proves to be only a necessary, not a sufficient, condition for avoidance. Neonates show evidence of sensitivity to depth (Slater & Morison, 1985), and 4-month-olds use depth information to control reaching responses (e.g., Yonas & Hartman, 1993). Subsequent explanations involved fear of heights as a mediator of avoidance (Bertenthal, Campos, & Barrett, 1984; Campos et al., 1978; Campos, Bertenthal, & Kermoian, 1992; Campos, Langer, & Krowitz, 1970), learning associations between the visual information for depth and the consequences of falling (Thelen & Smith, 1994), and learning that balance and locomotion require a floor beneath the body (Gibson & Schmuckler, 1989). On any of these accounts, infants should show adaptive avoidance responses regardless of the posture in which they are tested. A sheer drop-off has, by definition, an abrupt discontinuity in the floor beneath the body, generates a multitude of visual depth cues, and certainly puts infants at a great height above the floor of the precipice.

In contrast to all of these simple fact-based accounts, on the problem-solving approach to balance control, infants should avoid a drop-off when they have learned how to gauge the extent of their current region of permissible postural sway. Learning to learn would predict that infants should show more frequent and accurate avoidance responses in the postures with which they have experience combatting everyday threats to balance.

To test these predictions, we observed infants' responses at the edge of an adjustable gap in the surface of support (Adolph, 2000). As illustrated in Fig. 3.4, trials began with infants perched on a starting platform in a sitting or crawling posture. In both postures, they were urged to lean forward and stretch their arm over the gap toward a lure offered by their parents at the end of the landing platform. By rolling the landing platform along a calibrated track, we could vary the gap size from 0 cm to 90 cm in 2-cm increments. The smallest gaps were perfectly safe. Intermediate sized gaps were sometimes safe and sometimes risky depending on the postural condition and infants' current level of sitting or crawling skill. The largest gaps were impossibly risky. The 90-cm gap was comparable to the size of the standard visual cliff—essentially, a 3 ft long by 3 ft wide by 3 ft deep drop-off.
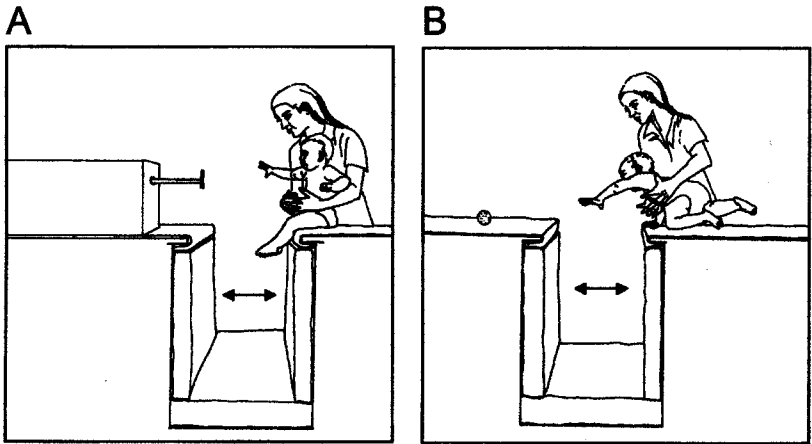
FIG. 3.4.   Platform with adjustable gap in the surface of support. (A) sitting
condition. (B) crawling condition. Experimenter (shown) followed along-
side infants to ensure their safety. Parents (not shown) encouraged infants
to span the gap from the far side of the landing platform. Reprinted from
Psychological Science, 11(4), 292. Copyright 2000 by American Psychological
Society. Adapted with permission.

Infants were 9.5 months old (plus/minus 1 week). All babies had more
experience sitting (M = 3.4 months) compared with crawling (M = 1.5
months). We reasoned that if infants are learning to learn about balance
control, they should respond flexibly and adaptively to novel threats to
balance. As one might expect, the infants' parents reported that they had
never placed their babies at the edge of a drop-off and encouraged them to
lean forward. To the contrary, parents did their best to keep their babies
away from the edge of the bed, changing table, kitchen counter, and so on.
Most important to the problem-solving framework, if sitting and crawling
are different problem spaces, then infants should respond more adap-
tively in their more experienced sitting posture.

We used an adaptation of a classic psychophysical staircase procedure
to estimate the relative amount of risk for each infant in each postural con-
dition (Adolph, 1995). In general, staircase procedures minimize the total
number of trials required to estimate a response curve for individual par-
ticipants. We varied the size of the test increments (in this case, gap size)
based on infants' responses on previous trials so as to place most of the
test trials along the slope of the response curve, where success ranges
from 100% to 0% rather than along the asymptotes, where success is either
100% or 0%. In this way, we could calculate a "motor threshold" or "gap
boundary" along the response curve to delineate the difference between
safe and risky gaps. We defined the boundary gap as the largest gap in-
fants could manage safely at a ≥ 67% criterion. By definition, gap sizes

smaller than the gap boundary were increasingly safe, and gap sizes larger than the boundary gap were increasingly risky. We reasoned that if infants respond adaptively to novel threats to balance control, they should attempt safe gaps smaller than their gap boundary and avoid risky gaps larger than their gap boundary.

Two experiments yielded the same result. As predicted by the problem-solving approach, adaptive responding depended on infants' experience with each posture, not their chronological age at testing (they were all the same age). Infants displayed more adaptive responses in their experienced sitting posture compared with their unfamiliar crawling posture at every risky gap size. In their experienced sitting posture, infants attempted safe gaps, but avoided risky ones.

Central to the problem-solving account, infants' responses were based on the relative amount of risk, rather than the absolute size of the gap. They matched the probability of avoiding to the conditional probability of falling (or, equivalently, the probability of attempting to the conditional probability of success). Yet, in their unfamiliar crawling posture, infants leaned too far over the brink and tumbled over the precipice into the experimenter's arms. In the first experiment, 32% of infants accurately avoided falling in the sitting condition, but fell at every risky gap size in the crawling condition. In the second experiment, 47% of infants responded adaptively in sitting, but fell at every risky gap size in the crawling condition. In their crawling posture, these clueless infants pitched forward repeatedly into the 90-cm-wide drop-off.

Results are consistent with the problem-solving approach. Experience with balance control allows infants to respond adaptively to a novel problem type. However, experience with an earlier developing skill does not transfer automatically to a later developing one. Learning is specific to the different problem spaces of sitting and crawling. The dissociation between postures belies previous accounts, suggesting that adaptive responses to disparity in depth of the ground surface depends on factual knowledge or simple associative learning, such as knowledge that the body cannot be supported in empty space, associations between depth information and falling, or the acquisition of fear of heights.

Cruising Over Gaps

Before infants walk independently, they cruise sideways in an upright posture, hanging onto furniture for balance. A long-standing assumption in the literature is that practice cruising teaches infants how to keep balance in walking (Haehl, Vardaxis, & Ulrich, 2000; McGraw, 1935; Metcalfe & Clark, 2000). Assumably, cruisers let go of the coffee table and walk frontward when they have learned to keep balance in an upright posture.

On the problem-solving framework, this assumption can only hold true if cruising and walking represent variants of the same balance control system—that is, if cruising and walking represent different problem types from the same problem space.

However, our casual observations of the infants in our laboratory led us to believe that cruising might be manually controlled. In other words, sideways cruisers appeared to keep balance and steer using their upper extremities rather than their legs. Despite the similarity in upright posture between cruising and walking, the key pivot and critical muscle synergies for maintaining balance in cruising may be in the arms, not the legs. The relevant environmental supports may concern the properties of the furniture ledge, not the properties of the floor. In fact, we hypothesized that infants may not take their legs and floor into account at all for gauging threats to upright balance while cruising.

To test the extent of the cruising problem space, we tested 11-month-old (plus/minus 1 week) cruising infants on our adjustable gap apparatus in two postural conditions (Leo et al., 2000). As illustrated in Fig. 3.5, the handrail condition was relevant for keeping balance with the arms. Infants were encouraged to cruise over a continuous floor with an adjust-
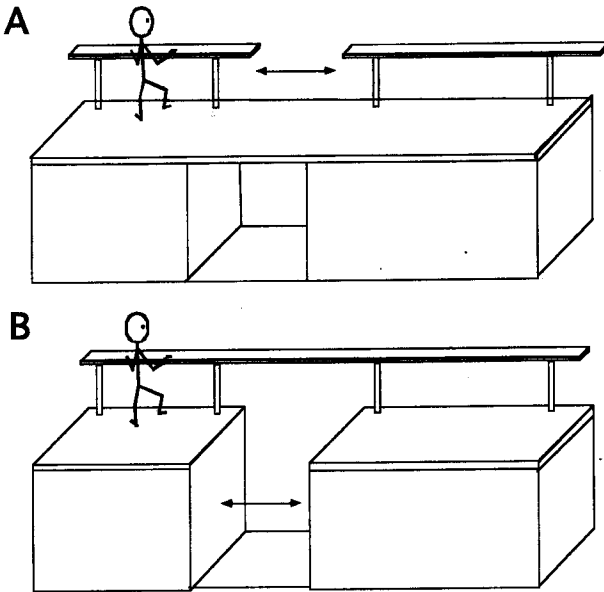

FIG. 3.5. Platform with continuous floor and adjustable gap in the handrail (top panel) or with adjustable gap in the floor and continuous handrail (bottom panel).

able gap in the handrail (0–90 cm). The floor condition was relevant for keeping balance with the legs. Infants were encouraged to cruise over a continuous handrail with an adjustable gap in the floor (0–90 cm). In both postural conditions, a research assistant showed infants the gap in the floor or the gap in the handrail at the start of each trial to ensure that they saw the size of the obstacle. Parents stood at the far side of the landing platform cheering their infants' efforts while an experimenter followed alongside infants to ensure their safety.

Because more proficient cruisers and infants with longer arms and legs might be able to cruise over larger gaps than less proficient, smaller infants, we used our modified psychophysical staircase procedure (Adolph, 1995) to normalize responses to the relative amount of risk for each baby in each postural condition. Thus, we could compare the adaptiveness of responses across infants and conditions.

Results are very clear. Infants' knowledge about balance control appeared to be limited to manual control of balance. At each risky gap increment, infants displayed more adaptive responses in the handrail condition compared with the floor condition. In the handrail condition, infants matched the probability of attempting to cruise to the conditional probability of success. They cruised over safe gaps in the handrail, but on risky gaps they gripped the starting handrail resolutely and refused to cross or they cruised to the end of the starting handrail and then crawled to the beginning of the ending handrail. The same infants, however, appeared oblivious to the fact that they needed a floor to maintain balance. In the floor condition, despite seeing the gap in the floor, most infants attempted to cruise over every risky gap increment, forcing the experimenter to rescue them as they clung to the handrail with their feet dangling into the precipice.

We serendipitously had the opportunity to observe a handful of infants who were slightly more motorically advanced. Between the time that we had scheduled them to come into the lab as sideways cruisers and the time that they arrived, the infants had begun to take a few independent forward-facing steps. When we tested these brand-new walkers on the adjustable gaps apparatus, they erred in both the handrail and floor conditions. At every risky gap increment, infants fell while attempting to walk from one end of the gap in the handrail to the other and while attempting to walk from one end of the gap in the floor to the other. Not only did new walkers ignore the relevant properties of the floor, they behaved as if they could no longer gauge the usefulness of the handrail for keeping balance.

The evidence suggests that cruising and walking are different balance control systems representing different problem spaces. Practice cruising helps infants gauge threats to balance in a cruising posture based on the

parameters that define manual control of balance. However, practice cruising does not lead to flexibility in walking where the problem space and relevant parameters are different.

Walking Over Bridges With Handrails to Augment Balance

In two subsequent experiments, we showed that relatively experienced walking infants can gauge when to use a handrail to augment their balance control (Berger & Adolph, 2003). Using a handrail is mandatory for keeping balance in a cruising posture, but using a handrail is optional in a walking posture. Appropriate use of a handrail in a walking posture would require infants to recognize that under normal walking conditons (e.g., on a flat, wide surface), a handrail is superfluous. However, in a tricky situation, where balance is precarious, manual support via a handrail can extend the region of permissible postural sway.

As illustrated in Fig. 3.6, we tested 16-month-old walking infants on wide and narrow bridges spanning a deep precipice. The precipice was 74 cm long, 76 cm wide, and 76 cm deep to the floor. Its interior was padded with foam to ensure infants' safety. The bridge widths varied from 12 cm to 72 cm wide in 6-cm increments. The narrowest ones were impossibly risky, like walking over a tightrope in a circus act; the intermediate bridge widths were like walking over a plank; and the widest bridge widths were no different from the solid platform. On some trials at each bridge width, a sturdy wooden handrail spanned the precipice along one edge of the bridge, but on other trials we removed the handrail. The experimenter presented each baby with a range of bridge widths and handrail presence in quasi-random orders for 24 trials. Parents stood at the far side of the landing platform to provide incentive for infants to cross, but they did not call infants' attention to the handrail.

Most of the infants in our sample had several months of walking experience. Thus, on the problem-solving framework, the infants should be sensitive to decrease in the size of their sway region on the narrowest bridges and recognize that the narrow bridges posed a threat to balance. Of special interest were the trials when the handrail was available. Infants might discover that they could expand the size of their sway region via the handrail and/or bolster their normal level of muscle strength for generating compensatory sways via manual support on the handrail.

Results are consistent with the problem-solving account. Infants' attempts to walk were scaled to bridge width, indicating that they perceived that the wider bridges were safer and the narrower bridges were riskier. Most important, there was an interaction between bridge width and handrail presence. All of the infants walked over the widest bridges on every trial regardless of whether the handrail was available, but on the narrow bridges infants attempted to walk only when there was a
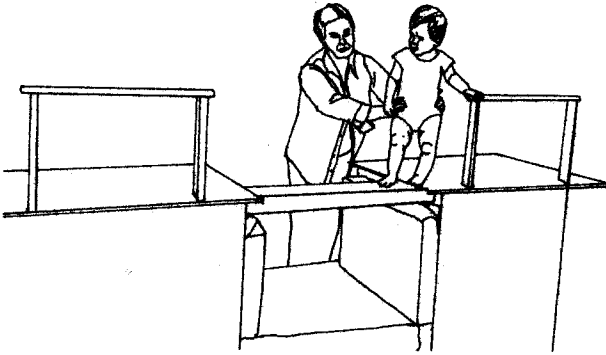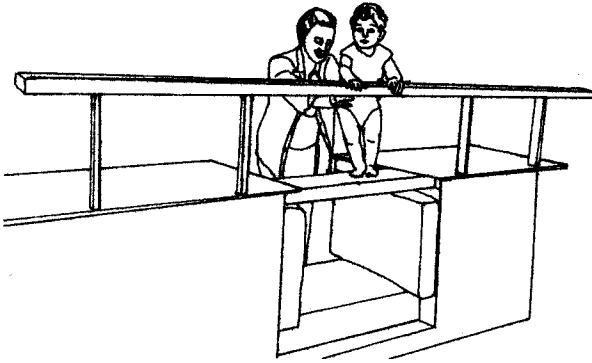
FIG. 3.6.   Platform with adjustable bridges spanning a precipice and re-
movable handrail. Experimenter (shown) followed alongside infants to en-
sure their safety. Parents (not shown) encouraged their infants to cross the
bridges from the far side of the landing platform. From *Developmental Psy-
chology, 39*(3), S. E. Berger & K. E. Adolph, "Infants Use Handrails as Tools
in a Locomotor Task," p. 596. Copyright 2000 by American Psychological
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handrail. When the handrail was unavailable, infants refused to leave
the starting platform. Most attempts were successful (94%), indicating
that infants' decisions were accurate. Although the experimenter vigi-
lantly followed alongside infants, she rarely had to rescue them from
falling into the precipice.

Infants' use of the handrail provides corroborating evidence that they
viewed the handrail as a potential means to augment balance. On wider
bridges, they either ran straight over the bridge to the landing platform
without touching the handrail or they tapped the handrail for a few milli-
seconds as they ran. On intermediate bridges, they held the handrail for

longer durations or slid their hand along the rail as they walked more gingerly. On the narrowest bridges, infants grabbed the handrail before leaving the starting platform and never released it. Many infants tested various strategies for using the handrail—usually inching along while turned sideways toward the rail, but occasionally facing frontward while holding the handrail with one hand or even holding the handrail behind their backs.

In a recently completed study with 16-month-old walking infants, we demonstrated that infants recognize that the handrail must be sturdy enough to support their weight to be used effectively as a tool to augment balance (Berger & Lobo, 2003). We varied bridge widths from 12 cm to 48 cm. A handrail was always available along one edge of the bridge, but on some trials it was made of sturdy wood and on others it was constructed of a pliant material. As in the earlier experiments, infants ignored the handrail on the wide bridge, but on the narrower bridges they were more likely to cross when the handrail was wood than when it was wobbly. Infants were also more likely to mouth the wobbly handrails and push them down while exploring from the starting platform.

Together these studies suggest that by 16 months infants are exquisitely sensitive to threats to upright balance and clever enough to discover new ways to protect themselves from falling. Infants used their repertoire of exploratory procedures (probing the bridges with their feet, taking a step or two onto the bridge before retreating to the starting platform) to determine whether bridges were safe for walking. Most striking, by using their exploratory procedures in the novel bridge/handrail situation (pushing/pulling the handrail, testing various body positions while holding the handrail, etc.), infants generated visual, tactile, and proprioceptive information to specify a larger, more stable sway region for crossing the narrowest bridges.

Crawling and Walking Down Slopes

We used an age-held constant research strategy for testing infants on gaps and bridges, then tested the adaptiveness of babies' responding in experienced versus unfamiliar postural conditions at the same relative amount of risk. We used a complementary longitudinal research strategy to test infants' responses on safe and risky slopes (Adolph, 1997). In the longitudinal research, we held locomotor experience constant at each test session and allowed age to vary across infants. Thus, we observed the infants repeatedly under fixed testing conditions to compare their responses over naturally occurring changes in body dimensions and skill levels at the same relative amounts of risk.

To test infants' responses to the novel problem of descending sloping ground surfaces, we constructed an adjustable slope apparatus from three

platforms connected by piano hinges (Fig. 3.7). Flat starting and landing platforms flanked a middle sloping section. By pumping a car jack, the slant of the middle section varied from 0° to 36° in 2° increments. The entire surface of the apparatus was covered with plush carpet to provide traction and cushioning if infants fell.

We observed one group of babies every 3 weeks for nearly a year, beginning on their first week of crawling and ending several weeks after they began walking. We observed a second group of babies at matched session times: in their first week of crawling, tenth week of crawling, and first week of walking. To estimate the relative amount of risk, we tested infants with the modified psychophysical procedure to estimate slope boundaries for each infant at each week of crawling and walking to a ≥ 67% criterion (Adolph, 1997). Thus, safe and risky slopes were redefined on a weekly basis relative to each baby's current level of crawling or walking skill. The same absolute degree of slope that was impossibly risky one week when crawling skill was poor might be perfectly safe the next week after crawling proficiency improved. The same degree of slope that was once safe for belly crawling might be risky for hands-knees crawling, a safe slope for hands-knees crawling might be risky for walking, and so on. Immense flexibility—the ability to solve novel problems on the fly— would be required for infants to scale their responses to the relative amount of risk given the dramatic changes incurred in their bodies and skill levels over the course of testing.

As predicted by the problem-solving framework, errors were related to the duration of infants' everyday locomotor experience. In their first
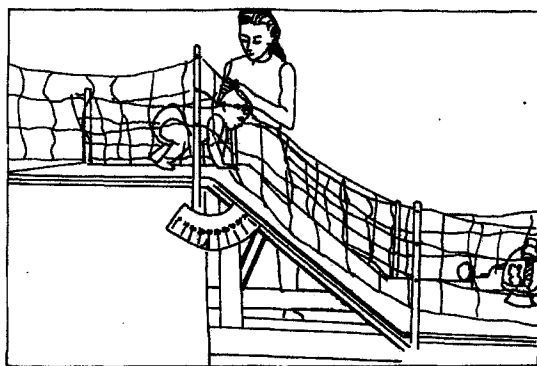

FIG. 3.7. Walkway with adjustable slope. Experimenter (shown) followed alongside infants to ensure their safety. Parents (not shown) encouraged their infants to descend the slopes from the far side of the landing platform. From *Learning in the Development of Infant Locomotion*, K. E. Adolph, 1997, *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251), p. 42. Copyright 1997 by the Society for Research in Child Development, Inc. Reprinted with permission.

weeks of crawling and walking, infants plunged repeatedly over the brink of impossibly steep slopes; average error rates were near to 75%. Gradually, over weeks of crawling and walking, infants' judgments geared in to the limits of their own abilities and error rates decreased. They used alternative sliding methods for descending risky slopes (sitting on their buttocks, backing down feet first, sliding head first prone like Superman) or they avoided descent entirely.

Like Harlow's (1949) monkeys solving discrimination and oddity problems, learning to cope with novel threats to balance was slow, difficult, and fraught with errors. On average, infants required 10 weeks of crawling or walking experience before errors decreased to 50% and 20 weeks or so for errors to decrease below 10%. Note that infants were not simply learning that a helpful adult would rescue them (like a common game of jumping from the kitchen counter into a parents' arms). Although the same experimenter caught infants as they plunged over the brink of risky slopes in their early weeks of crawling and walking, over repeated weeks of testing, infants became more cautious and responded more adaptively, not more reckless and blasé.

Infants' responses represented flexibility of learning, not merely the effects of repeated practice on slopes. Neither infants in the experimental group who were tested every 3 weeks nor the infants in the control group who were tested only at three matched session times had experience descending playground slides or other slopes outside the laboratory. Despite repeated testing involving hundreds of trials on slopes in the experimental group, learning was not dependent on slope experience. The control group of infants who were tested only at three matched session times did not have extensive experience on laboratory slopes. Infants in the control group displayed the same error rates at each matched session time as the infants tested every 3 weeks.

Most dramatic, learning was specific to each postural milestone. The same infants who had refused to crawl down risky slopes as experienced crawlers plunged heedlessly over the brink when they stood up and began walking. There was no evidence that learning about balance control transferred from crawling to walking. Learning was no faster the second time around. Error rates were just as high in infants' first week of walking as they were in their first week of crawling, and the learning curves for crawling and walking were parallel.

In fact, infants showed posture-specific responses from trial to trial. At the end of each walking session, we tested babies in six back-to-back trials on the steepest 36° slope. On the first two trials, we started infants in their unfamiliar upright posture. New walkers attempted to walk over the edge of the precipice. On the next two trials, we started infants in their old, familiar crawling posture. They responded adaptively by sliding down or

avoiding descent. Moments later on the last two trials, when we started them in their unfamiliar walking posture, again infants walked over the brink and fell into the experimenter's arms.

Explanations based on simple associate learning, fear of heights, and facts about ground surfaces or infants' bodies cannot account for the results from our longitudinal observations of infants over weeks of crawling and walking. On any of those accounts, infants should have responded the same way to the same absolute degree of slope, and learning should have transferred from crawling to walking. However, we obtained the opposite results. What then do infants learn? On the problem-solving account, infants are learning to learn about balance. They are learning to identify the perimeters of a new problem space, acquire the exploratory procedures for calibrating balance online, and thereby learning to gauge the extent of their current region of permissible postural sway.

Walking Down Slopes Loaded With Weights

Consistent with the problem-solving framework, the longitudinal data suggested that experienced infants can recalibrate the settings of relevant balance control parameters to take into account naturally occurring changes in their functional body dimensions and skills. We put this suggestion to the test by experimentally manipulating infants' bodies and skills (Adolph & Avolio, 2000).

We dressed 14-month-old walking infants in a tight-fitting Velcro-covered vest. Slung over both of the infants' shoulders were a pair of removable Velcro-covered shoulderpacks loaded with feather-weight poly-fil or lead-weight pellets (see Fig. 3.8). Both pairs of shoulderpacks could be quickly exchanged by fixing and unsticking the shoulderpacks to the Velcro vest. The weight of the feather-packs was negligible and only made infants larger through the chest. The lead-weighted shoulderpacks increased infants' mass by 25% and raised their center of mass several centimeters above their bellies. With their center of mass displaced upward, destabilizing torque increased. As a consequence, infants' balance was more precarious. On average, we reduced the size of the angle of permissible postural sway by 30%. In effect, we turned relatively maturely proportioned and proficient walking infants into more top-heavy and poorly skilled walkers.

To make infants' task really challenging, we encouraged them to walk down safe and risky slopes. A new adjustable slope apparatus, operated via a drive-screw from a garage door opener, allowed the degree of slant to vary from 0° to 88° in 4° increments. The purpose of testing infants on slopes was to exacerbate the effects of the weights and to allow us to assess how accurately infants could scale their responses to
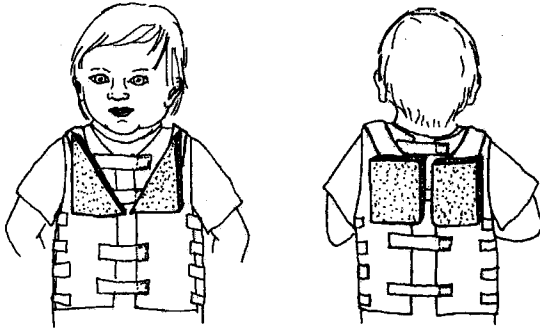
FIG. 3.8.   Velcro vest with removable shoulderpacks.

the relative amount of risk. We ran two staircase protocols in tandem, switching from feather to lead packs quasi-randomly from trial to trial. Infants were observed over 58 to 87 trials, with 4 trials placed at each safe and risky increment. We used a 75% success criterion for identifying the slope boundary for each infant in each shoulderpack condition. The study design constituted a strict test of infants' ability to gauge their region of permissible postural sway. Because we switched between staircase protocols in a quasi-random fashion, infants could not know whether their shoulderpacks were loaded with feathers or lead—whether balance was normal or precarious—until the start of the trial when the experimenter put them down on the starting platform and they could feel themselves sway.

Indeed the lead weights affected walking skill. Infants could walk down steeper slopes in their feather-weight packs compared with their lead-weighted packs (4°–16° difference). Thus, very shallow slopes were safe and very steep slopes were risky. Because slope boundaries varied for each baby between shoulderpack conditions, slopes in the intermediate range were sometimes safe and sometimes risky depending on the shoulderpack condition. As illustrated by the vertical arrow in the left panel of Fig. 3.3B, the same absolute degree of slope could mean different things from trial to trial in the two conditions.

Most impressively, infants treated the same absolute degree of slope as safer in their feather packs, but as riskier in their lead packs. Consistent with the problem-solving account, they were more likely to attempt to walk down slopes in the intermediate range when they were wearing their feather-weighted packs than when they were wearing their lead-weighted packs. Recalibration was nearly perfect (approximating the perfectly superimposed curves in the right panel of Fig. 3.3B). Infants displayed only slightly more errors in their novel lead weights compared

with their feather weights and only on slightly risky slopes a few degrees steeper than their slope boundaries.

Summary

To summarize, a series of separate experiments supported the predictions of the problem-solving framework for understanding the development of flexibility. Infants' ability to respond adaptively to novel threats to balance depended on the duration of their everyday experience with balance control, not their chronological age. The course of learning was slow and spanned several months of everyday practice. Consistent with learning to learn, but inconsistent with simple associative pairing, adaptive responding was based on relative amount of risk, rather than absolute stimulus increments. Once flexibility was achieved, infants could discover new solutions to novel problems online in the midst of the task. However, adaptive responding to threats to balance was limited to the postures with which infants had extensive experience. Learning did not transfer to new postures in development.

WHAT INFANTS MUST LEARN AND HOW

Flexibility

The central question, of course, in any study of transfer concerns what was learned in the first place that did or did not transfer. I am proposing that learning to learn in infant motor skill acquisition is the same as learning to learn in any task—whether in monkey discrimination problems, chess, basketball, or cooking. To achieve flexibility, learners must define the perimeters of the problem space, identify the relevant parameters for operating within the problem space, and acquire the tools for calibrating the settings of the parameters online.

In this case, infants must map out the limits of each problem space for each new postural milestone in development. They must identify the relevant balance control parameters for each posture that define the problem space, including the key pivots around which their bodies rotate, the relevant parts of their bodies and muscle groups for generating compensatory sway, changing vantage points for viewing the layout of the ground ahead, and various sources of perceptual information. Finally, they must acquire the appropriate exploratory movements—swaying, looking, touching, and testing various strategies—for recalibrating the settings of the appropriate parameters so that they can gauge the size of their current region of permissible postural sway from moment to moment.

How then might learning work? Although the duration of infants' everyday experience with balance and locomotion is a good predictor of adaptive responding in the laboratory tasks, duration of experience tells us nothing about mechansisms. In fact, the actual content of infants' locomotor experience is unknown. To date all theorizing about experience-related mechanisms has been completely unconstrained by empirical facts. Researchers have treated experience like chronological age. Experience is calculated simply as the number of days that have elapsed between the onset date and the test date, just as chronological age is calculated as the number of days elapsed between birth and the test date. Elapsed time, however, is not an explanatory variable without a description of what exactly infants experienced during the passage of time.

Content of Everyday Experience

To redress the deficiency in the literature concerning the nature of infants' everyday experiences with locomotion, my colleagues and I are in the process of conducting a series of diary studies designed to obtain detailed descriptions of infants' everyday experiences with balance control during stance and locomotion (Adolph, 2002). To date the samples include infants living in elevator buildings in an urban setting in New York City and infants living in single-family homes in the suburbs of Pittsburgh. We use a daily checklist diary technique to track the appearance and disappearance of motor skills in infants' repertoires. Each day parents check off whether infants have displayed each of 54 motor skills beginning shortly after infants are born and ending several months after they begin walking (Adolph, Biu, Pethkongathan, & Young, 2002; Biu et al., 2003; Young, Biu, Pethkongkathon, Kanani, & Adolph, 2002). We use a call-in telephone diary procedure to track crawling infants' whereabouts in 15-minute time blocks from the time babies wake up until the time they go to bed over the course of several weeks (Chan, Lu, Marin, & Adolph, 1999; Chan, Biancaniello, Adolph, & Marin, 2000). We have designed several varieties of foot switches to count walking infants' steps as they travel freely around their homes and out of doors (Adolph, 2002). In each study, researchers draw detailed blueprints of infants' homes to obtain information about the places infants visit, the surfaces they travel over, the paths of their locomotor excursions, and the distances they travel between locations.

The diary studies showed vast individual differences on every measure. Infants had different opportunities for learning in their environments, different levels of access to opportunities provided by their caregivers, and different physical abilities and skill levels that might allow

them to exploit the various opportunities afforded. For example, infants differed in terms of the available floor space in their homes (New York City infants lived in tiny apartments, whereas suburban infants in Pittsburgh lived in larger, multilevel homes), experience with outdoor surfaces (New York City infants had less experience on grass, but more on concrete), experience with stairs (New York City infants lived in elevator buildings and were delayed in their access to stairs), and so on. Babies began crawling and walking at the wide range of ages that are typical of healthy infants, meaning that infants were subject to any age-related differences in motivation to explore the environment, separate from caregivers, and the like. Infants' bodies and skill levels also spanned the wide ranges typical of healthy infants. Some babies were built like big round Buddhas, and others were slender, small, and wiry.

Despite the range in individual differences, several factors were common across infants. Every baby was exposed to massive amounts of tiny mundane experiences with balance, presented in variable contexts, and distributed widely over time during the course of each day and across days and weeks. These factors—massive doses, equally salient stimulus dimensions and consequences, variable training contexts, and distributed practice schedules—are exactly the factors that facilitate flexibility of learning in laboratory studies of skill acquisition. In short, the diary studies suggest that if researchers could design a practice regimen to promote flexibility in infants' balance control based on what investigators have learned from 100 years of laboratory research on skill acquisition, the training schedule would look much like infants' actual everyday experiences with balance.

For example, we found that crawling infants spent 41% of their waking day (approximately 5 hours), on average, on the floor engaged in active, independent balance control in sitting and crawling postures. In addition, crawlers spent 17% of their waking day (approximately 2.6 hours) in passive locomotion—being carried in caregivers' arms or wheeled around in strollers. They traveled over 6 to 12 different indoor and outdoor surfaces each day at an average speed of 27 to 43 meters/hr. Their total daily crawling distance was between 60 and 188 meters (the length of two football fields). Based on crawlers' average step length, we calculated that babies experienced 1,000 to 3,200 crawling steps each day.

After infants begin walking, opportunities for learning expand dramatically. Our diary studies showed that walking infants spent 50% of their waking day (approximately 6 hours) on the floor maintaining balance in sitting, standing, and walking postures. The step counters showed that babies took approximately 500 to 1,500 steps/hour—9,000 steps/day. Based on infants' average step length, toddlers' maximum total daily distance was 2,700 meters (the length of 29 football fields).

Epochs of Experience.   Exposure to balance constraints during infants' everyday life occurs in truly massive doses. For nearly half of their waking day, infants fight gravity unsupported by caregivers or furniture. Each tiny crawling and walking step, each body sway and shift in position, is in a sense like a little training trial of exposure to the challenges of maintaining balance. Compiled over the hours, days, and weeks that characterize infants' protracted periods of experience with each postural milestone, infants' everyday practice regimen is best described in terms of epochs of experience.

In terms of opportunities for learning, our preliminary results provide an astounding contrast compared with earlier research on learning to learn. Recall that Harlow's (1949) learning set studies were a relatively simple preparation. Subjects were posed with discrimination and oddity problems. To acquire flexibility in Harlow's model system, adult monkeys required experience with hundreds of problem types, with 10 blocked trials in each type for thousands of trials. In contrast, in the more complex model system of human infants acquiring balance control, our diary studies show that babies get that many trials before lunch. To put the sheer amount of infants' experience into context, such consistently high levels of exposure are similar to the practice regimens necessary for expert performance in concert pianists and Olympians (Ericsson & Charness, 1994; Ericsson, Krampe, & Tesch-Romer, 1993; Ericsson & Lehmann, 1996).

No One-Trial Learning.   Infants' experience is happy and uneventful. We found no evidence of one-trial learning about balance nor any evidence that any particular kind of experience was critical. Despite common-sense intuitions that serious falls might play an important role in learning about balance, most infants sail through their infancy unscathed. Infants in both the crawling and walking diary studies occasionally fell hard enough that they cried and required comforting after a bad spill. However, only 1 of 18 infants tracked longitudinally required medical attention after a fall. Similarly, in earlier studies, where infants were tracked prospectively or parents provided retrospective reports, few infants incurred serious falls during everyday locomotion, and those that had behaved no differently on laboratory tasks compared with those that had not (e.g., Adolph, 1995; Adolph, 1997, 2000; Scarr & Salapatek, 1970). After their accidents, infants dragged their casts and bruises over the brink of steep slopes and cliffs in the same proportions as the rest of the samples.

Variable Practice.   Infants' practice with balance control occurs under wildly variable conditions in terms of the surfaces they travel over and stand on, the places in which the surfaces are located, and the events that precipitate the visit. A key to flexibility in balance control is to refrain from

forming simple associative pairings so as to identify the critical features that allow online problem solving to occur. Variable contexts may help discourage simple associative pairings. Recall that in Harlow's (1949) studies, the critical factor for learning to learn was practice with varying pairs of shapes that hid the raisin, not the details of any particular problem type. Similarly, laboratory studies of motor skill acquisition in human participants show that learning under a variable practice regimen takes longer compared with blocked practice, but variable practice leads to a broader range of transfer when participants are challenged with novel problems (Gentile, 2000; Schmidt & Lee, 1999). Thus, variable contexts in everyday stance and locomotion may promote flexibility in infants' balance control.

Distributed Practice. Infants' experience with locomotion is not like an enforced march. Rather, babies crawl and walk in bursts of activity—a dozen steps or 100 steps during a quick foray from one place to another—separated by periods of quiet stance when they stop to play, manipulate objects, or interact with a caregiver. Moreover, experience with balance in sitting, crawling, cruising, standing, and walking emerges into infants' repertoires with fits and starts. Infants may sit independently on one day but not on the next or pass criterion for walking for a few days then fail to pass for the next few.

Laboratory studies of skill acquisition suggest that such distributed practice schedules may facilitate learning by providing rest periods to dissipate fatigue and boredom and allow infants to recover their motivation to move. Moreover, distributed practice may provide time to consolidate learning in working memory (Gentile, 2000; Schmidt & Lee, 1999).

SUMMARY

In summary, the diary studies of everyday experiences with balance and locomotion are consistent with a problem-solving framework for understanding the development of behavioral flexibility. The demands for flexibility in balance control are enormous. Changing body dimensions, changing skill levels, and changing environments change the biomechanical constraints on balance from moment to moment. Happily, the opportunities for learning are also enormous. Healthy infants immersed in the rich and varied challenges of everyday life are well prepared to acquire the requisite levels of flexibility (and specificity) that they need to promote adaptive responding under continually changing conditions.

ACKNOWLEDGMENTS

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