CHAPTER FOUR

Motor development: how infants get into the act

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## Overview: motor actions and psychological function

Motor development is truly amazing. In their first year of life, infants acquire the ability to direct their eyes at targets, support their bodies against gravity, grasp and manipulate objects, and locomote across the room. One reason why these accomplishments appear so amazing is that motor actions are directly observable. Whereas we must infer developments in perception and cognition on the basis of infants' overt behaviors, development in motor skills require no inferential leap from observable behavior to underlying competence. When infants turn their head to gaze up at a parent's smiling face, stretch out an arm to reach for an attractive toy, and maintain balance while toddling across the room, the overt motor performance is direct evidence of their developing skill.

Perhaps not so readily apparent are the links between motor skills and other psychological functions. Motor actions are not merely a matter of muscles and biomechanics. Perception and cognition are integral to the real-time control of movement (Adolph & Berger, 2005, in press; Bertenthal & Clifton, 1998; Gibson & Pick, 2000). Perception informs infants about which movements to do and how to execute them to suit the constraints of the current situation. Perceptual information guides infants' eyes, hands, and bodies toward the target, and perceptual systems provide feedback about the consequences of the movement. Cognition—learning, thinking, remembering, and means–ends problem-solving—helps infants to discover new solutions for challenging motor problems and to avoid repeating mistakes that they have tried in the past. Action, in turn, provides new information for perceptual systems and new grist for cognition. Every movement points both backward and forward, generating information about the consequences of the prior movement and specifying which movements to do next.

Motor skills are also linked with developmental changes in perception and cognition. As Piaget (1952) and Gibson (1988) pointed out, the acquisition of new motor skills provides infants with new sources of information about the world. The development of **eye–head control** provides infants with opportunities to learn about events and the location of objects and surfaces. **Looking** is probably the most pervasive mode of access to information about things at a distance. The development of **manual skills** invites a new world of learning about objects and surfaces. Once infants can reach, grasp, and manipulate objects, they can bring things to their eyes and mouth for additional exploration and see what objects look like from multiple angles. Once they can stretch out an arm to explore a surface, they can discover what things feel like and whether surfaces can support their weight. The development of independent **locomotion** allows infants to learn about places and the objects and surfaces that populate various locations. Now, infants can position their own bodies to see what is around the corner or under the table, exert change on the environment by fetching and carrying objects, and assert new forms of emotional independence by leaving their caregivers to explore on their own (Figure 4.1).

Perhaps most amazing are the deeper psychological implications of basic motor skills. Integral to the seemingly simple acts of looking, reaching, and walking are what E. Gibson (Gibson, 1997; Gibson & Pick, 2000) eloquently termed the **hallmarks of psychological development**. Motor actions involve **agency** (knowledge of a distinct self who can effect change on the environment), **prospectivity** (gearing actions to the future), **behavioral flexibility** (adapting behaviors to variable and novel circumstances), and **means–ends problem-solving** (finding new ways to achieve one's goals). Although these psychological achievements are central to every domain of development, Gibson's hallmarks are perhaps best illustrated in the motor domain where researchers can directly observe psychology in action.

The chapter is divided into three sections, each representing an action system that infants master in the first year of life: eye–head control, manual skills, and locomotion. Typically, infants acquire these action systems in sequence, so that development proceeds from head to toe and the earlier developing action system serves as a building block for the later developing one. Developments in postural control underlie the entire progression because looking, reaching, and locomotion can only emerge from a stable postural base (see changing postures in Figure 4.1). In each section of the chapter, we illustrate the importance of motor development by highlighting the reciprocal relationship between motor actions and psychological development. Drawing on examples from classic and recent research, we focus on the facilitative effects of motor development. We show how infants' emerging motor skills expand the scope of their effective environment and thereby enlarge and enrich their psychological world. A pervasive theme is the central role of motor experience in facilitating developmental change. We also illustrate
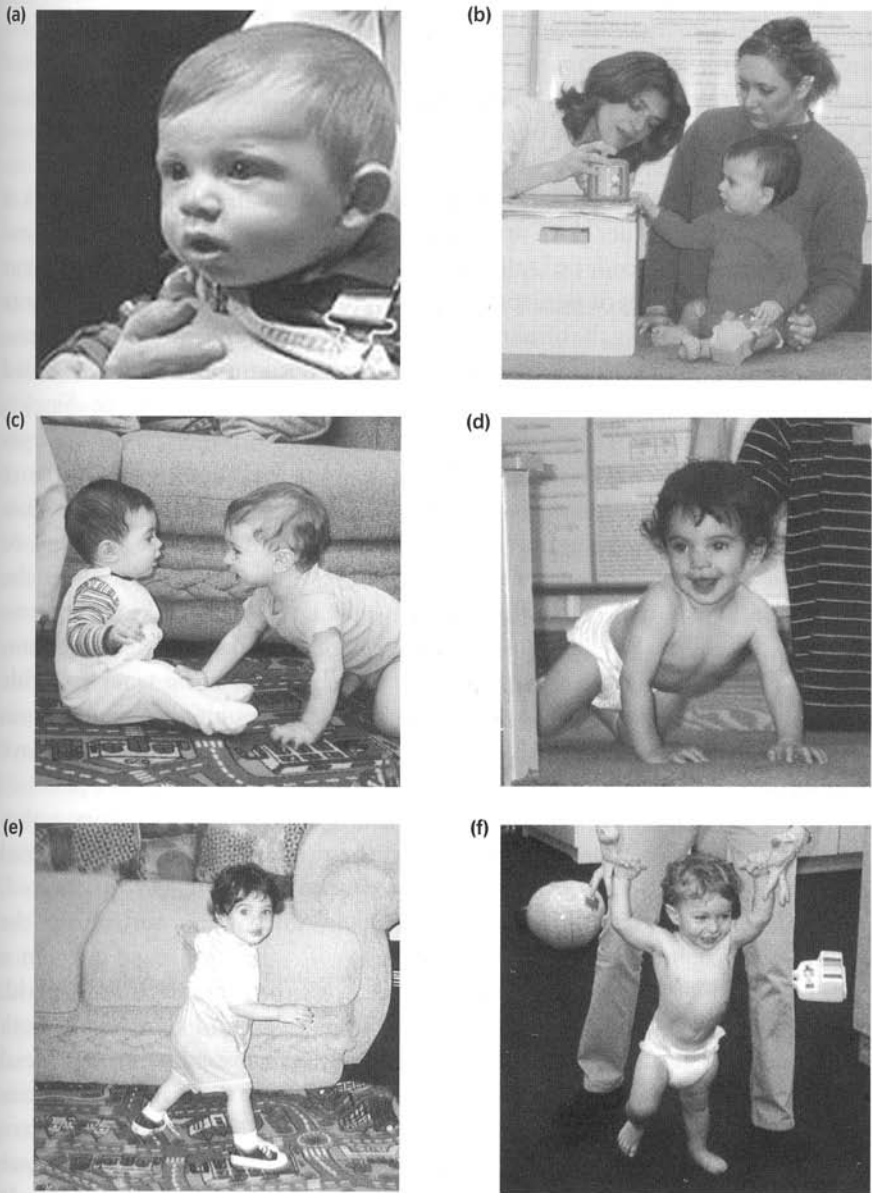
Figure 4.1 Developmental changes in infants' action systems. Postural control is a prerequisite for each new skill. (a) Eye-head control allows visual exploration by looking. (b) Sitting and reaching provide new means for interacting with objects. (c, d) Sitting and crawling give infants new vantage points and new access to varied locations. (e, f) Cruising (moving sideways along furniture) and walking provide a higher vantage point and different ways of interacting with objects, people, and places (pictures courtesy of Karen Adolph).

the flip side of the developmental story: how the hallmarks of psychological growth are expressed in the context of motor action.

Eye–head control

For many years, developmental researchers have treated infants' eyes as a perceptual system rather than an action system. Part of this traditional view stems from several decades of reliance on infants' looking time as a dependent measure: Most studies of perceptual and cognitive development with infants use preferential looking, habituation, and violation of expectation paradigms. Indeed, many recent studies have juxtaposed looking with **action-based measures** such as reaching (Munakata, McClelland, Johnson & Siegler, 1997, p. 704) and **active object search** (Keen, 2003, p. 79), as if the eyes are perceptual whereas the arms are motor. However, looking is no more passive than reaching. Although looking may serve as a convenient window into perceptual and conceptual processes, it is a motor action (Adolph & Berger, in press). Infants must move their eyes and heads to look at the displays (rather than at the ceiling or their bellies and feet) and looking-time measures depend on how long infants aim their eyes in the various directions. Eye-tracking studies make this point very clearly because the traces provide a record of infants' eye movements. The single data point that results from a looking-time study is actually a summary of dozens of exploratory eye movements.

Looking is not only an exploratory system. It is also a performatory action system that infants can use to respond to and initiate changes in the external environment, in this case, the social environment (Gibson, 1988). Indeed, looking is one of infants' first means for social interaction and one of the first signs of agency. Through looking behaviors, infants begin to gain a sense of a distinct self with intentions and powers that can act on the world. In normal face-to-face interactions between infants and caregivers, both social partners initiate and respond to each other's eye movements, facial expressions, vocalizations, and gentle touches. When the social contingencies are broken, for example, by a caregiver presenting a still face rather than a reciprocally moving and interacting one, infants stop directing their gaze at their partner, stop smiling, and may become distressed (Gusella, Muir & Tronick, 1988).

Like all action systems, eye–head coordination develops. At first, looking is mostly opportunistic. Young infants have difficulty focusing visual attention on interesting objects and events because they lack the muscle strength to hold their heads up against gravity and they lack the coordination to turn their heads in unison with their eyes (Daniel & Lee, 1990). Newborns can turn their heads from side to side while resting on their stomachs or backs,

but they cannot lift their heads off the floor for extended periods of time (Bly, 1994). When they are held upright, their large heads loll. By 2–3 weeks after birth, infants' muscles have become strong enough to lift their chins from the floor while prone. By 5–10 weeks, infants can lift their heads and chest from the floor. By 3 months, infants can hold their heads steady while propping themselves on their arms in a prone position and when held upright on their parents' laps (Bly, 1994). Now, infants need not wait for objects to fall into their line of sight. Instead, they can control where they are looking.

Smooth pursuit is an especially complex type of eye movement. To move their gaze at the same speed as an object, infants must control their eye movements prospectively. They must anticipate and predict where the object will be next. At 1 month of age, infants can smoothly follow a moving object with their eyes for short periods of time, but only if the conditions are just right (Aslin, 1981; Rosander & von Hofsten, 2000; von Hofsten & Rosander, 1996). For example, objects must be large and move slowly along a predictable path (von Hofsten & Rosander, 1997). Moreover, infants' heads must be held in place by a caregiver's hands or supported by cushions because infants do not have sufficient control to manage their heads on their own. Smooth pursuit improves rapidly over the next few months, so that looking at moving objects shows longer periods of smooth pursuit and shorter periods of corrective jerky saccades (Figure 4.2A). With practice, infants become better able to follow smaller, faster objects (Phillips, Finoccio, Ong & Fuchs, 1997; Richards & Holley, 1999; Rosander & von Hofsten, 2002).

Prospectivity in looking requires not just improvements in smooth pursuit and head control, but also coordination between eye and head movements. While following a moving object, sometimes the head may move too slowly and the eyes may need to compensate. Initially, eye and head movements are not well coordinated (von Hofsten, 2004; von Hofsten & Rosander, 1997). Weeks after infants can track moving objects smoothly with their eyes, they begin to make large tracking movements with their heads. However, initially their heads lag so far behind the target that they must put their eyes ahead of the target to keep it in view. As a consequence of their poor eye–head coordination, infants show a decrease in tracking precision. By 4–5 months, they can move their eyes and heads together to follow objects smoothly (Rosander & von Hofsten, 2004).

Experience moving the eyes and head to track objects facilitates infants' object knowledge. When a moving object disappears behind an occluder (imagine a ball moving behind a square screen), infants must possess a rudimentary knowledge of objects to understand that the object continues to exist and to anticipate when it will reappear on the far side. Normally, 6-month-olds exhibit more anticipatory eye movements than 4-month-olds while tracking an object as it moves behind an occluder, and the older

infants' eye movements are faster. However, only 2 minutes of experience tracking an object moving on an unoccluded trajectory was sufficient to boost 4-month-olds' performance to that of 6-month-olds when tested with the object moving behind an occluder (Johnson, Amso & Slemner, 2003).

Even at the same age, the ability to keep the eyes on a moving target predicts infants' level of object knowledge (Johnson, Slemmer & Amso,
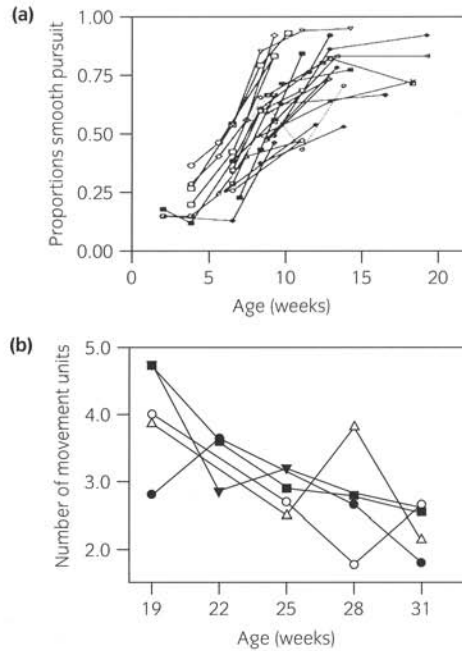
Figure 4.2 Developmental improvements in looking, reaching, and locomotion. (a) Improvements in smooth pursuit, the ability to smoothly track moving objects with the eyes, from 3 to 20 weeks. Curves show developmental trajectories of individual infants. Adapted from von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences, 8,* 266–272, with permission from Elsevier, copyright © (2004). (b) Improvements in reaching from 19 to 31 weeks of age. Fewer movement units imply fewer corrections and straighter reaching paths. Curves show developmental trajectories of individual infants. Adapted from von Hofsten, C. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior, 23,* 280–292, with permission of the Helen Dwight Reid Educational Foundation. Published by Heldref Publications, 1319 18th Street, NW, Washington, DC 20036–1802. www.heldref.org. Copyright © (1991). (c) Improvements in crawling proficiency (indexed by velocity) over weeks of experience. Solid curve represents infants who crawled on their bellies prior to crawling on hands and knees. Dashed curve represents infants who skipped the belly crawling period. Adapted from Adolph, K. E., Vereijken, B. & Denny, M. A. (1998). Learning to crawl. *Child Development, 69,* 1299–1312, with permission from Blackwell Publishing. (d) Improvements in walking proficiency over weeks of experience (indexed by step length). Each symbol represents one infant's data. Adapted from Adolph, K. E., Vereijken, B. & Shrout, P. E. (2003). What changes in infant walking and why. *Child Development, 74,* 475–497, with permission from Blackwell Publishing.
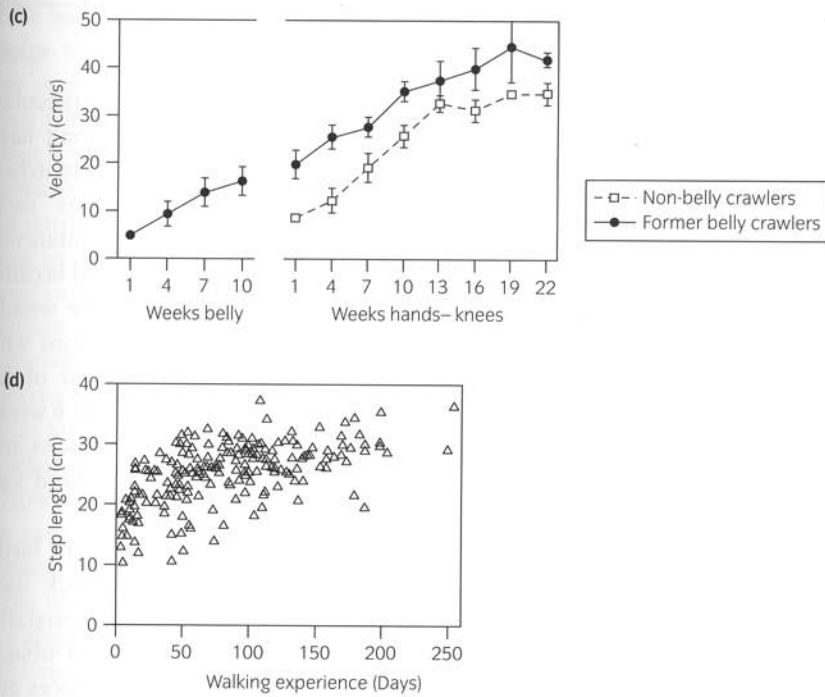
(c)

(d)

Figure 4.2 continued.

2004). At 3 months of age, some infants spontaneously watched the visible ends of a rod as it moved back and forth behind an occluder during an initial familiarization period. Other infants directed more of their eye movements toward the occluder or the background. Thus, the former group showed higher levels of visual object exploration. They were also more likely to show increased looking times at test displays of two end bits of rods, suggesting that they had perceived that the rod was complete as they tracked its trajectory during familiarization. The latter group, who had looked at the occluder rather than the moving object, were more likely to show increased looking to a test display of the complete rod, suggesting that they had failed to detect object unity during the initial familiarization period.

Given the powerful facilitative effects of only 2 minutes of experience moving their eyes in a laboratory looking task, the benefits of everyday experiences with looking must be enormous. By some estimates, 2-month-old infants have logged more than 200 hours of visual experience and have made over 2.5 million eye movements (Johnson *et al.*, 2003)! By 3.5 months, infants have executed between 3 and 6 million eye movements as they scan, track, and explore their visual surrounds (Haith, Hazan & Goodman, 1988). Developing motor skill with eyes and head presents infants with increasing opportunities to learn by looking.

Manual skills

Many misconceptions about motor development stem from our vernacular. We talk of 'fetuses kicking' and 'infants reaching' because we don't have common expressions to describe the spontaneous flails, wiggles, twitches, arches, thrashes, and so on that characterize so many of infants' early limb movements. Most fetal 'kicks' felt by mothers are really spontaneous movements of arms, head, trunk—and legs—against the uterine wall because the fetus cannot fully extend its body parts in the tight space of the womb. Most of infants' early 'reaches' are really spontaneous arm extensions with no ability or intent to grasp an object. Spontaneous motility is one of the pervasive features of early motor development. Movements begin at 6 weeks of gestation, from the instant that fetuses acquire rudimentary muscles and neural circuitry (Moore & Persaud, 1998). Fetuses and infants spend vast amounts of time in motion.

The earliest examples of infants' manual behaviors occur before birth. Fetuses flail their arms, wiggle their fingers, form a fist, and suck their thumbs (Prechtl, 1985, 1986). Manual exploration also begins prenatally. Approximately 2/3 of fetal hand movements are directed toward objects and surfaces—the umbilical cord, the uterine wall, and their own faces and bodies (Sparling, van Tol & Chescheir, 1999). Spontaneous arm movements continue after birth and persist in high frequency throughout the first year (Thelen, 1979). Infants bang their arms and hands against surfaces, flap their arms up and down, bend and straighten their elbows, rotate their hands in circles, and wave their fingers.

Spontaneous manual activity can quickly become goal-directed when harnessed by the appropriate experimental arrangement. For example, 2- to 8-month-olds increased the frequency of their arm flails when the movements activated an engaging slide show (Lewis, Alessandri & Sullivan, 1990). The shift from spontaneous to instrumental activity reflects a sense of agency. Infants' facial expressions were neutral as they flailed their arms spontaneously during baseline activity. Their expressions showed interest, joy, and surprise as they explored the contingency between their arm movements and the slide show and then worked to maintain the reinforcement. Their expressions conveyed anger when the contingency was broken in an extinction period and infants showed interest and joy—but not surprise—when the contingency was reinstated. The facial expressions of yoked controls tended toward neutral across conditions, suggesting that it was the sense of control—their own power over the environment—that was reinforcing, not simply the slide show.

The development of reaching depends on postural control (Bertenthal & von Hofsten, 1998). The problem is not sufficient strength to lift the arms; the impediment to reaching is sufficient strength and control to support the rest

of the body as the arms lift or swing (Adolph & Berger, 2005). Infants cannot engage in manual activities while their heads loll or their trunks collapse; they cannot reach when their arms are needed to support their bodies. Thus, when left to their own powers, infants' first goal-directed reaches appear at about 4 months while lying on their backs, at 5 months while lying on their stomachs propped on one arm, and at 6–8 months while sitting with their legs outstretched in a 'V' (Bly, 1994; Rochat, 1992). Around the time infants begin to sit independently, they also begin to show coordinated manual and visual exploration: They finger objects and rotate them in front of their faces, alternate between mouthing and looking, and transfer objects from one hand to the other (Rochat, 1989). Better sitting abilities predict more sophisticated behaviors such as leaning forward to grab objects, using both right and left hands interchangeably, and retrieving objects across a wider range of space (Rochat & Goubet, 1995).

However, with the right kind of external postural support, even newborns can extend their arms in the general direction of a target (Amiel-Tison & Grenier, 1986; von Hofsten, 1982, 1984; von Hofsten & Ronnqvist, 1993). In the most popular paradigms, infants are strapped high around the chest to a slightly reclined board with their heads propped upright by tiny side cushions, or are supported on their parents' laps with the adults' hands holding up their torsos (Figure 4.3). While supported, infants begin reaching for stationary objects between 12 and 18 weeks of age (Berthier & Keen, 2006; Clifton, Muir, Ashmead & Clarkson, 1993) and for moving objects at around 18 weeks (von Hofsten, 1979, 1980). Usually, infants' first supported reaches end with object contact rather than capturing the object in their grasp.

As with the eye–head system, reaching and grasping show developmental improvements in prospective control. Initially, infants' reaching movements
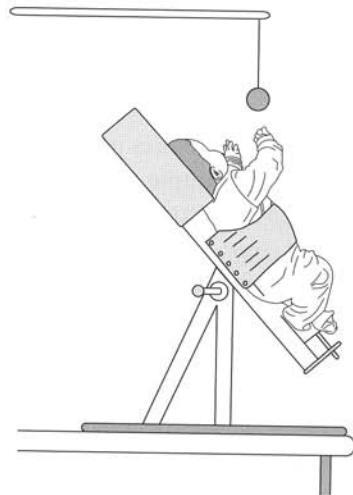
Figure 4.3 Typical experimental set-up to test reaching in young infants. The reclining seat and head cushions provide external postural support for infants who cannot yet sit independently. The chest strap leaves infants' hands free for reaching objects. Adapted from von Hofsten, C. (1982). Eye–hand coordination in the newborn. *Developmental Psychology, 18,* 450–461, with permission from APA.

are jerky and composed of several corrections as infants guide their hands toward the goal. Reaching becomes progressively smoother and straighter until, at approximately 31 weeks of age, infants' reaches resemble the adult form: a large movement to bring the hand to the vicinity of the target and a second smaller movement for the grasp (von Hofsten, 1991) (Figure 4.2b). Toward the end of the first year, prospective control of reaching is sufficiently well developed for infants to catch objects moving at different speeds (van Hof, van der Kamp, Caljouw & Savelsbergh, 2005) and to catch moving objects as they emerge from behind an occluder (van der Meer, van der Weel & Lee, 1994).

Prospective control of grasping develops during the same time period. Infants' first grasps are little more than accidental swipes, but by 5 months of age, infants change their grip configuration to match the size and shape of target objects (Newell, Scully, McDonald & Baillargeon, 1989). By 7.5 months, they preform the orientation of their hands to match the orientation of a target dowel (Witherington, 2005). By 9 months, they open their hands to match an object's size and start closing it in anticipation of contacting the object (von Hofsten & Ronnqvist, 1988). By 10 months, their grasps are so accurate that they can pincer-grip small objects between their thumb and fingers (Gesell, 1952).

New opportunities for learning abound after infants solve the problem of postural control and free up their hands for exploration. They can discover a new world of objects, surfaces, and the relations between them. For example, 6- to 10-month-old infants explored a wooden cube by scratching and picking it and a sponge cube by squeezing it (Bourgeois, Khawar, Neal & Lockman, 2005). They used rubbing, picking, pressing, and slapping movements differentially to explore rigid, spongy, net, and liquid tabletop surfaces. Most interesting, infants related the objects to the surfaces differentially with their exploratory movements. They rubbed the cubes against the rigid tabletop, pressed the cubes into the spongy tabletop, and banged the wooden cube against the rigid and net tabletops. The 10-month-olds' actions were the most discriminating.

Exploration is intrinsically rewarding. The ability to learn through manual manipulation makes infants eager for more interactions with objects and surfaces. For example, a clever manipulation—sticky Velcro mittens—allowed 3-month-olds to reach, grasp, and manipulate Velcro-covered toys (Needham, Barrett & Peterman, 2002). With their transformed manual skills, these normally floundering infants picked up objects and brought them to their eyes and mouths for exploration. After practicing 10 minutes a day for 2 weeks, infants looked at objects, swatted them, mouthed them, and exhibited more alternations between looking and mouthing than a control group of infants without manual motor experience. Motor experience also facilitates intermodal perception of objects. At 5.5 months of age, some infants have poor object manipulation skills (like a typical 3-month-old without sticky mittens)

and others have quite developed skills. Infants with more highly developed object-manipulation skills looked differentially at displays of single- and multiple-impact object events (a spoon banging against a bowl vs. marbles rattling around a glass jar) depending on whether the sound from a central loudspeaker matched the event (Eppler, 1995). Poorly skilled infants looked equally at both displays.

The ability to manipulate objects, explore surfaces, and relate objects to surfaces lays the groundwork for improvements in cognitive function; most notably, the means–ends reasoning involved in **tool use** (Lockman, 2000; Willatts, 1999). Using a tool requires infants to carry out a series of steps. First, they must notice a discrepancy between what they can do and their goal. Second, they must find a new means to resolve the discrepancy by incorporating an external object or environmental support into their action plan. Finally, they must enact the appropriate behaviors to implement the tool and achieve their goal (Berger & Adolph, 2003).

One example of means–ends problem-solving is infants' ability to extend the limits of their reach by using nearby sticks, hooks, and rakes to drag the desired object closer (Bates, Carlson-Luden & Bretherton, 1980; Brown, 1990; Chen & Siegler, 2000; Leeuwen, Smitsman & Leeuwen, 1994). A more familiar example is how infants use a spoon to feed themselves (McCarty, Clifton & Collard, 1999, 2001). At 9 months of age, infants recognize the spoon as a tool, but they do not plan their reaching actions appropriately. Thus, they may grab a spoon by the bowl end instead of the handle end or grasp the handle palm up and then awkwardly rotate their hand to eat the food. By 18 months, their means–ends skills are so developed that they know exactly which end of the spoon to grab and they configure their grip most efficiently palm down. By 24 months, infants show behavioral flexibility in their tool use: they modify their grip to eat from a spoon with a bent handle (Steenbergen, van der Kamp, Smitsman & Carson, 1997).

Locomotion

Locomotion is the most outwardly dramatic of infants' emerging action systems. Parents herald infants' first walking steps as the transition from infancy to childhood and celebrate the occasion with the same joy and gravity as infants' first words. Parents might be less likely to recognize, however, the protracted period of locomotor development that precedes their infants' first steps, and less likely to appreciate the psychological concomitants and consequences of independent mobility (see Adolph & Berger, 2005, in press; Bertenthal & Clifton, 1998; Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein & Witherington, 2000; Gibson & Schmuckler, 1989).

The view that locomotor development is a series of orderly stages is simply wrong. Each infant can exhibit an individual trajectory of locomotor achievements. Typically, the ability to move the whole body begins in the first 6 months of life as infants roll from their bellies onto their backs, pivot in circles while prone, hoist themselves to a sitting position and flop back onto their bellies, and so on (Bly, 1994). Many infants discover idiosyncratic ways of translating their bodies through space: bum-shuffling in a sitting position, crabbing on their backs, and log rolling. Some infants begin crawling with their bellies on the floor for part of each crawling cycle (Adolph, Vereijken & Denny, 1998). Before acquiring a hands-and-knees gait, they may 'combat crawl' using their arms for propulsion and dragging their legs behind, 'inchworm crawl' by alternately pushing their chest off the floor then springing forward onto their bellies, or 'swim' using all four limbs at once. Other infants skip the belly-crawling period and proceed straight to hands and knees (or hands and feet) at approximately 8 months of age. Still other infants never crawl; their first successful mobility is in an upright position.

Improvements in locomotor skill are experience dependent. For example, with each week of experience, infants' crawling becomes faster and their movements become larger. Experience is a better predictor of crawling skill than infants' age or body dimensions. In fact, infants who belly crawled are more proficient in their first weeks on hands and knees than infants who never belly crawled (Figure 4.2c), despite the fact that former belly crawlers and sole hands-and-knees crawlers are the same age, on average, when they begin crawling on hands and knees and their bodies are the same size (Adolph et al., 1998). Similarly, experience pivoting, rocking on hands and knees, and other precursory prone movements facilitate improvements in the speed and size of hands-and-knees crawling movements, despite differences between the earlier and later developing movements in the patterns of inter-limb coordination and the body parts used for support and propulsion.

At approximately 7–13 months of age, infants pull themselves to a standing position and begin cruising; they move sideways in an upright position while holding onto the wall or furniture for support (Bly, 1994; Frankenburg & Dodds, 1967). Around their first birthday, they begin taking independent walking steps (Bly, 1994). Note, however, that the normal age range for walking onset is wide—11–15 months (Frankenburg & Dodds, 1967). As with crawling, improvements in walking are experience driven. At first, infants' balance is so precarious that their steps are tiny and their legs are splayed wide and toes pointed outward for extra stability; their cadence is choppy because they keep both legs on the floor for as long a time as possible and one leg in the air for as short a time as possible (Bril & Breniere, 1989, 1993). Over the first few months of walking, step length increases, step width and external rotation decrease, the percentage of the gait cycle spent with both feet on the floor decreases, and the percentage of the gait cycle spent

with one foot in the air increases (Figure 4.2d). Walking experience is a stronger predictor of improvements in infants' walking skill than their age or body dimensions (Adolph, Vereijken & Shrout, 2003).

What might infants experience while rolling, pivoting, crawling, and walking that facilitates improvements in locomotor proficiency? Or, for that matter, what might infants experience during balance and locomotion that provides them with new opportunities for learning? One thing is clear: experience is not a forced march or rote repetition. Under the most optimal conditions, while traveling over the smooth path of a laboratory floor, infants start and stop at will and their crawling and walking steps are highly variable from cycle to cycle (Adolph *et al.*, 1998; Adolph *et al.*, 2003).

Home diaries, step counter devices, and video tracking methods show that the quantity and variety of infants' locomotor experience is truly staggering. Crawling and walking infants spend approximately half of their waking day on the floor engaged in balance and locomotion (5–6 hours of activity out of 12 hours awake). During most of the time that infants are free to locomote, they do not. Nonetheless, in short bursts of locomotor activity, crawlers manage to take 1028–3198 crawling steps/day and cover a daily distance of 60.4–187.8 m (66–206 yards)—about the length of two football fields (Adolph, 2002). In 16 minutes of free indoor play—during most of which time they are stationary—walking infants average 586 steps and 3–4 falls. By extrapolation, walkers average 13 185 steps and 90 falls a day and travel a daily distance of 39 football fields (Garciaguirre & Adolph, 2006). Every day, infants crawl or walk through nearly every room in their homes and travel over 6–12 different ground surfaces (Adolph, 2002; Garciaguirre & Adolph, 2006).

One consequence of experience with balance and locomotion is a new source of information about the self. As infants sit, stand, crawl, or walk, their body sways around its base of support. Each swaying movement generates a flow of optic information that specifies the direction and speed of the movement—the self in motion. When necessary, infants can use this information to produce a compensatory postural sway in the opposite direction.

Researchers can test infants' ability to use visual information for self motion in a 'moving room,' a life-size enclosure that rolls back and forth along a track (Lee & Lishman, 1975; Lishman & Lee, 1973). Infants sit, stand, or walk as the room moves around them. Room movement in one direction creates optic flow that simulates a postural sway in the same direction. To compensate, infants sway in the opposite direction. New walkers sway so forcefully that they stagger and fall, but older children and adults show less dramatic postural responses (Schmuckler, 1997; Stoffregen, Schmuckler & Gibson, 1987; Wann, Mon-Williams & Rushton, 1998). Locomotor experience serves to differentiate peripheral optic flow from the side walls from radial flow from the front wall. For example, pre-crawling 8-month-olds

swayed in response to both side and front wall movement, but 8-month-olds with crawling experience showed adult-like responses by swaying primarily after movement of the side walls (Higgins, Campos & Kermoian, 1996). In adults, the two types of optic flow structure serve different functions: peripheral flow for balance and radial flow for steering (e.g., Stoffregen, 1986; Warren, Kay & Yilmaz, 1996). In a continuously oscillating room, older, more experienced infants timed their swaying movements more closely to the room movements than did younger, less experienced infants (Barela, Godoi, Freitas & Polastri, 2000; Bertenthal, Rose & Bai, 1997; Delorme, Frigon & Lagace, 1989).

A second consequence of experience with balance and locomotion is increased behavioral flexibility. Experience facilitates infants' ability to cope with novel, variable, and challenging tasks. In the most famous paradigm, infants are tested at the edge of an apparent drop-off on a **visual cliff** (e.g., Gibson & Walk, 1960) (Figure 4.4a). Infants begin on a narrow board looking down into an abyss 90 cm (3 feet) deep, while parents at the far side encourage them to cross (the entire apparatus is covered with glass to ensure the infants' safety). In a frequently cited study, locomotor experience predicted adaptive avoidance responses (Bertenthal, Campos & Barrett, 1984; Campos, Hiatt, Ramsay, Henderson & Svejda, 1978). At the very same age at testing (7.5 months), infants with 6 weeks of crawling experience, on average, were likely to avoid the apparent drop-off, but infants with 2 weeks of crawling experience, on average, were likely to cross. However, the role of experience in avoiding the deep side of the visual cliff has been hotly debated (Bertenthal & Campos, 1984; Rader, Bausano & Richards, 1980; Richards & Rader, 1981). Moreover, the visual cliff has several methodological limitations (Adolph & Berger, in press). The size of the drop-off is fixed, so researchers cannot test the precision of infants' responses or ask whether infants scale their motor decisions to the size of the challenge. The safety glass presents mixed messages: The visual cliff looks dangerous, but feels safe. In fact, because infants quickly learn that the apparatus is perfectly safe (albeit creepy), avoidance attenuates and they can only be tested in one or two trials (Campos *et al.*, 1978; Eppler, Satterwhite, Wendt & Bruce, 1997).

One way to address the methodological problems with the visual cliff is to test infants on a real cliff with adjustable dimensions. Adolph (2000) constructed such a device, a **veritable cliff** (Figures 4.4b, c). In this case, the apparatus challenged infants with gaps in the surface of support, varying in 2-cm increments from 0 to 90 cm (36 inches). The largest gap width had dimensions equivalent to that on the standard visual cliff. In lieu of the safety glass, an experimenter rescued infants if they began to fall into the precipice. Because infants could be tested over dozens of trials, psychophysical methods determined the accuracy of their responses.

On the gaps apparatus, experience maintaining balance and locomotion predicted infants' level of behavioral flexibility (Adolph, 2000). However,
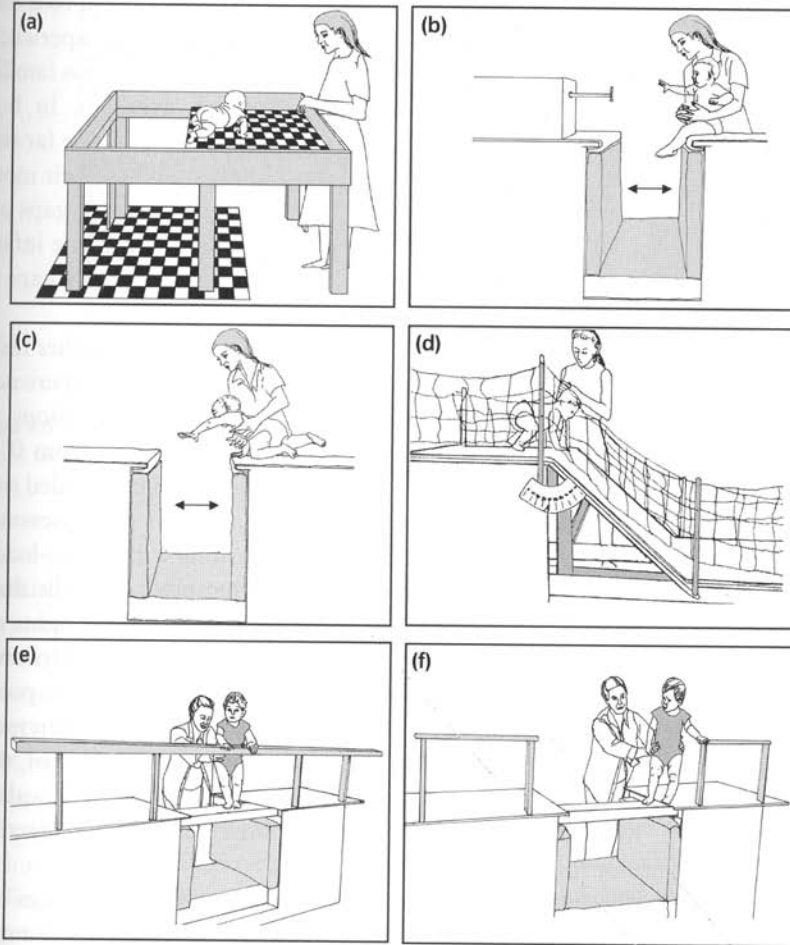
Figure 4.4 Various experimental paradigms for testing infants' response to novel locomotor challenges: (a) The visual cliff. Parent (shown) coaxes infant from far side of glass table. Adapted from Walk, R. D. & Gibson, E. J. (1961). A comparative and analytical study of visual depth perception. *Psychological Monographs: General and Applied, 75*(15, Whole No. 519). (b–c) Adjustable gap in the floor to test infants in sitting and crawling postures, respectively. Experimenter (shown) follows alongside infants to ensure their safety. Parents (not shown) encourage infants from the far side of the gap. Reprinted from Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 11*, 290–295, with permission from Blackwell Publishing. (d) Adjustable sloping walkway to test infants in crawling and walking postures. Experimenter (shown) follows alongside infants to ensure their safety. Parents (not shown) encourage infants from the far side of the slope. Reprinted from Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251), with permission from Blackwell Publishing. (e, f) Bridges with and without handrails. Experimenter (shown) follows alongside infants to ensure their safety. Parents (not shown) encourage infants from the far side of the precipice. Reprinted from Berger, S. E. & Adolph, K. E. (2003). Infants use handrails as tools in a locomotor task, *Developmental Psychology, 39*, 594–605, with permission from APA.

learning did not transfer from an earlier developing action system to a later developing one. Each infant was tested in two postures, an experienced sitting posture (15 weeks of sitting experience, on average) and a less familiar crawling posture (6 weeks of crawling experience, on average). In both postures, their task was to lean across the gap to retrieve a toy on the far side. In their more experienced sitting posture, infants closely matched their motor decisions to the actual probability of falling: They attempted safe gaps and avoided risky ones. In their less familiar crawling posture, the same infants showed poorly adapted decisions: they attempted impossibly risky gaps on trial after trial, including the widest 90-cm (36-inch) gap.

A similar pattern of results holds for other action systems and other tasks. For example, in both cross-sectional and longitudinal studies, experienced crawling and walking infants showed finely adapted motor decisions for descending shallow and steep slopes (varying in 2° increments from 0° to 90°) (Figure 4.4d). They attempted safe slopes but slid down or avoided risky ones (Adolph, 1995, 1997). Infants could even update their risk assessment after experimental manipulation of their body dimensions with a lead-loaded vest (Adolph & Avolio, 2000). They correctly attempted to walk down steeper slopes on trials when their vests were filled with feather weights and shallower slopes on trials when their vests were loaded with lead. However, in their first weeks of crawling and walking, infants' decisions were poorly adapted and they attempted slopes far beyond their capabilities. When tested week after week, the same infants who could discern the limits of their abilities as crawlers plunged headlong down risky slopes as new walkers (Adolph, 1997). In sum, experience promoted flexibility for the practiced action system but not for the newly acquired one.

Learning from locomotor experience typically requires more than one exposure, even when the experience seems highly salient. For example, learning from falling is not automatic or immediate. When 15-month-olds fell head first into a 'surprise' foam pit, they required several trials before they learned that the particular patch of ground would not support their weight (Joh & Adolph, 2006) (Figure 4.5). The foam pit was situated in the middle of an otherwise solid walkway. Although the deformable area was distinctly marked by salient visual cues (a bumpy surface with rounded edges, a colored and patterned cloth covering, prominent landmarks around the laboratory), on their first trial, all participants walked straight into the foam pit and fell. Surprisingly, infants continued to fall into the foam pit on subsequent trials (7 trials, on average) before selecting an alternative method of locomotion or avoiding the risky area. A quarter of the 15-month-olds never learned, and fell on 16 test trials. Only 11% of the infants learned after their first exposure. The number of 1-trial learners increased with age. By 39 months, 50% of children learned in 1 trial and nearly all adults showed 1-trial learning. Perhaps falling is so commonplace for younger children that they do not link the visible appearance of the ground surface with the consequence of loss of balance.
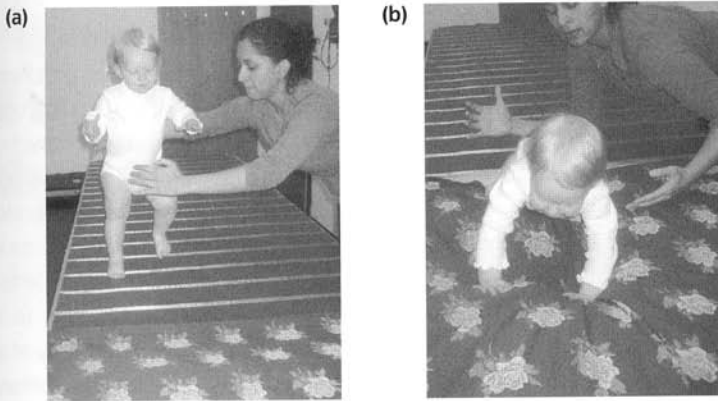
Figure 4.5 Apparatus to test learning from falling. (a) Infant walking over solid platform toward foam pit and (b) falling headlong into the foam cushions (pictures courtesy of Amy Joh).

A third consequence of locomotor experience is the opportunity to discover new means for achieving end goals. Although means–ends problem-solving is typically studied in manual tasks, in locomotor tasks new means can involve motor actions with the whole body. In Köhler's (1925) classic studies, chimps retrieved a banana hanging from the ceiling by stacking boxes on top of each other, seriating pedestals, or using a pole to vault themselves toward the ceiling. Human infants were initially not as clever as the adult chimps and tried vainly to obtain the lure (food or an attractive toy) by merely reaching toward it without using the boxes or pedestals as a means to an end (McGraw, 1935). After weeks of training, infants learned that the various pedestals and boxes could be arranged systematically to allow access to the lure.

In a more recent example of whole-body problem-solving, 16-month-old infants used handrails to augment their balance while crossing narrow and wide bridges (Berger & Adolph, 2003) (Figures 4.4e, f). The bridges (12–72 cm, 5–28 inches) spanned a deep precipice between two platforms. On some trials a wooden handrail was available and on others it was not. When bridges were wide enough to permit safe passage, infants ran straight across without noticing the handrail. When bridges were impossibly narrow, infants remained on the starting platform regardless of whether the handrail was present. But on bridges of intermediate widths, infants crossed only when the handrail was available and not when the handrail was absent. Moreover, infants took the material composition of the handrail into account when evaluating its use as a tool to extend their abilities. They crossed intermediate bridges more often with a solid wooden handrail than with a wobbly foam one (Berger, Adolph & Lobo, 2005).

SUMMARY

The amazing parade of new motor skills in infants' first year of life illustrates more than a triumph of muscles over gravity. Motor skill acquisition involves perception, cognition, and vast amounts of learning. Motor skills facilitate developments in other psychological domains because the ability to move the various parts of the body provides infants with new opportunities for learning. Motor skills are unique in psychological development because movements are directly visible. Motor actions share with achievements in other domains the central hallmarks of psychological development. What is unique to motor skill acquisition is the opportunity for researchers, parents, and teachers to directly observe these hallmarks in action: displays of agency and infants' discovery of a sense of self, examples of behavioral flexibility and infants' ability to adapt their behaviors to changing circumstances, and invention of new means as infants acquire new ways to achieve their goals.