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CHAPTER 4

Motor Development

KAREN E. ADOLPH and SCOTT R. ROBINSON

Our nature lies in movement. Complete calm is death.

—Blaise Pascal

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LEARNING TO MOVE AND MOVING TO LEARN

The average toddler can run circles around the world's most sophisticated robots. Sure, robots can dole out pharmaceuticals, build cars, vacuum your house, and collect rocks from the surface of Mars. But, robots cannot yet match the effortless variety and adaptive flexibility of motor behaviors executed in the course of everyday

activity by the average 18-month-old (Pfeifer, Lungarella, & Iida, 2012).

By 18 months of age, toddlers can coordinate their limbs to navigate living room clutter, run into mother's arms, crawl under a chair, or climb up a flight of stairs. They can control their arms to pound a peg or pet a cat and configure their hands to unscrew the lid of a water bottle or grasp a tiny bite of cracker between thumb and finger. They can synchronize torso, head, and eyes to examine a toy in hand, peer under the table, or gaze at a caregiver. They can coordinate tongue and jaw to eat a snack or speak their intentions. And whereas robots can still only perform particular tasks in particular environments, toddlers multitask in variable environments: They walk, talk, look around, and interact with objects and people all at the same time (Franchak, Kretch, Soska, & Adolph, 2011). What babies have got that robots have not is the ability to produce an endless

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variety of behavior flexibly tailored to the constraints of the immediate situation (Pfeifer, Lungarella, & Iida, 2007; Stoytchev, 2009). Moreover, infants' motor skills improve as their bodies and environments are changing. In contrast to robots, infants learn in the context of continual development (Berthier, Rosenstein, & Barto, 2005). This chapter is about how children learn the amazing array of motor skills—locomotion, manual skills, facial actions, and exploratory movements—that make them superior to the world's most sophisticated robots.

Chapter Overview

In reviewing work on motor development, we aim to interest readers from every area of developmental science. How so? Rather than writing a boutique chapter geared toward researchers who specialize in motor development, we use research on motor development to address central concepts and methodological issues that have challenged developmental scientists for centuries. We argue that the study of motor development can yield fresh insights into processes of learning and development. Motor behavior can take the lead in developmental research and partner with work in seemingly disparate domains by considering developmental phenomena as embodied in the reality of children's growing bodies, embedded in the practical exigencies of a physical environment, intimately involved in social interactions, and reflective of cultural influences.

Our strategy is to focus on 10 general developmental issues that are broadly relevant to developmental science and aptly illustrated with examples drawn from research on motor development. The issues are loosely organized into framing sections on embodied movement, embedded action, and enculturated interaction.

1. We address the issue of *incidental activity and consequential function* by describing the myriad forms of spontaneous behavior expressed in fetuses, infants, and young children while awake and asleep. Although incidental activity is not intentionally goal directed, it can still serve crucial functions in the process of development.
2. One of the oldest yet still relevant questions posed by developmental researchers concerns the developmental relation between similar behaviors displayed at different ages. We suggest three ways of understanding *developmental continuity: precursors, historical antecedents, and primitives*. Each interpretation is embraced by a large community of researchers, but none are wholly satisfying.
3. Intraindividual *variability represents both problem and promise* for developmental researchers. Usually treated as a statistical nuisance in other psychological domains, research on motor development considers intraindividual variability to be integral to development. Intraindividual variability can reflect inconsistency in motor control, be a natural outcome of dynamic stability, and provide the raw material for selection, refinement, and innovation of behavior.
4. *The passage of time* is emblematic of development, but researchers have evaded the central problem of how time contributes to developmental change. Rather than treating elapsed time as a developmental mechanism, we suggest that researchers should quantify the succession of events that constitute experience and endogenous changes in the body and nervous system. Similarly, understanding the true shape of developmental change requires researchers to sample behavior at the appropriate density on a developmental scale.
5. *Adaptation and developmental diversity* in behavior highlight the fact that behavioral development is an embodied process. Motor behavior involves movement of the body, but the body is continually changing and no two bodies are the same. Short-term changes in the body pose biomechanical challenges for motor control, and long-term diversity among bodies requires development to be flexible and adaptive.
6. Development does not proceed in a vacuum. Infants and children develop in a physical environment, and *learning by doing involves exploration of the environment*, sometimes from a distance and sometimes up close.
7. Efficient behavior requires advance *planning and innovating*—in other words, *prospective control*. Rigid motor programs are not viable in a normal, variable environment. Prospective control often entails a succession of motor strategies, involving initial formulation of a plan of action, modification of the plan in the face of unexpected contingencies, and making a new plan when initial strategies fail.
8. How do children recognize what they can and cannot do in a given situation? We argue that possibilities for action depend on the fit between the current status of the body and the environment. Since the body and environment are continually in flux, affordances for action are also continually changing. Children learn to choose appropriate actions by *perceiving*

and generalizing affordances for action. The process involves learning to learn rather than learning fixed solutions.

9. Development always occurs in a social and cultural context. But researchers' understanding of development is biased, relying on data drawn mostly from children of Western, educated, middle-class families. Cross-cultural comparisons show that growing up in *other cultures leads to other paths* of development. Human motor behavior is far more varied and malleable than is generally appreciated, and cultural variation in basic childrearing practices contribute to variable patterns of motor development.
10. Motor behavior is often relegated to an early and isolated chapter in books on developmental psychology. But growing evidence shows that motor development can instigate a *developmental cascade* of events that extend beyond mere movement of the body, effecting changes in perceptual, cognitive, and social development.

This list of 10 general developmental issues illustrated by motor behavior represents a departure from typical review chapters that involve chronicles of age-related changes in motor skills, head-to-toe descriptions of action systems, detailed investigations of particular action systems or tasks, historical overviews, or treatises on particular theoretical approaches to motor development (e.g., Adolph & Berger, 2011; Clark & Oliveira, 2006; Corbetta, 2009; Keen, 2011; Schmuckler, 2013a; Smitsman & Corbetta, 2010; Thelen, 2000; Vollmer & Forssberg, 2009; von Hofsten, 2007, 2009). For researchers who do not study motor behavior, our discussion of difficult and controversial developmental issues in the context of motor development—a field in which they have no stake—may enable them to consider the implications for their own areas of inquiry with fresh eyes.

We aim to broaden the appeal of research on motor development by selecting examples that highlight the breadth, excitement, and rigor of the research. For researchers in the field, we focus more heavily on work that appeared after the publication of the previous two *Handbook* chapters (Adolph & Berger, 2006; Bertenthal & Clifton, 1998) and include less familiar examples from animal work and robotics. We provide examples from various points in the lifespan, but focus on infancy because that is the period of development when most of this research has been conducted. For readers new to the field, we hope to impart a sense of the beauty and wonder of motor behavior.

Behavioral Development Is Motor Development

A quick scan of the two most prominent journals in our field—*Developmental Psychology* and *Child Development*—reveals relatively few studies of motor development compared with studies of cognitive, social, language, personality, perceptual, and emotional development. (Since 1980, only 5.2% of 5,617 journal articles on these topics were related to motor development.) This wallflower status was not always the case. In the first half of the 20th century, research on motor development dominated the literature. Many of the early pioneers focused primarily on motor development (Gesell, 1946; McGraw, 1945; Shirley, 1931).

Why did motor development fall out of favor? One possible explanation is that the early researchers focused too heavily on developmental norms; once the normative sequence of behaviors was described, there seemed little else to do. Figure 4.1a shows a standard chart of infants' motor milestones, *de rigueur* for every introductory text and doctor's office, but useless for understanding developmental processes beyond the obvious conclusion that motor skills improve with age. A second possibility is the advent of the cognitive revolution; researchers' focus on the inner workings of the mind drew attention away from the outer workings of the body. The richness and scope of work by Piaget, Vygotsky, and others eclipsed the traditional maturation-based theories that dominated motor development during its heyday (Gesell, 1933; Shirley, 1933b). Although the early pioneers wrote extensively about the roles of perception, cognition, social interaction, motivation, and affect in motor skill acquisition (Gesell & Thompson, 1934; McGraw, 1935; Shirley, 1933a), these ideas fell to the wayside. What survived in the introductory texts were normative data and milestone charts.

Despite a recent resurgence of interest in motor development, it still remains a rarity in developmental science. This situation is ironic because motor behavior is one of the broadest domains of development. All behavior is motor behavior. Thus, the study of motor development is really the study of behavioral development, a topic that should be of interest to most developmental scientists. Moreover, research on motor development offers unique advantages compared with other areas of research. Motor behavior is directly observable. In other domains, the phenomena of interest—children's thoughts, percepts, motivations, and so on—are hidden and must be inferred from observable behavior. Even brain imaging and physiological measures take their meaning from observable

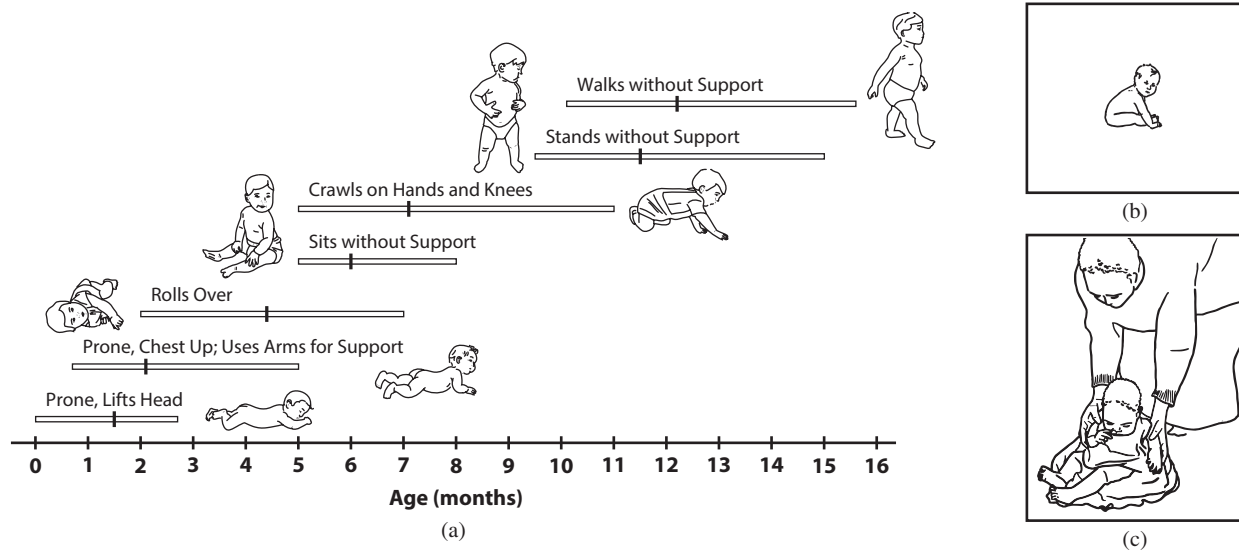


Figure 4.1 Depictions of infant motor milestones. (a) Standard motor milestone chart showing progression of postural and locomotor skills and age norms for each skill. Horizontal bars represent the normative range of skill onset; vertical lines show average age of first occurrence. As is typical in such depictions, skills are ordered by chronological age, implying a maturational sequence, and infants are shown isolated from the environmental context. Data from Bayley (1969) and Frankenburg, Dodds, Archer, Shapiro, and Bresnick (1992). (b) Image from the title page of Myrtle McGraw's (1945) classic text on motor development portrays an isolated infant in a sitting position floating in empty space. (c) A more embedded and enculturated depiction of sitting in a West African infant. The infant is shown in the full environment context, supported by the ground, wrappings, and a caregiver. Adapted from *How Children Develop* (p. 192), by R. S. Siegler, J. DeLoache, and N. Eisenberg, 2011, New York, NY: Worth.

motor behavior. In contrast, *behavior* is the phenomenon of interest in motor development. With motor behavior, researchers can directly observe change over multiple nested time scales. The millisecond timing of a saccade or a reach is nested within a series of eye and arm movements that play out over seconds, and these changes in turn are nested within changes in the speed, smoothness, and accuracy of those movements that take place over larger time scales of days, weeks, months, and years. Indeed, research on motor development has led developmental science in the recording and analysis of time-based behavioral data (e.g., McGraw & Breeze, 1941). Long before brain imaging and eye tracking came into vogue, motor development researchers were analyzing fine-grained data on infants' movements, the muscle actions that produce those movements, and the resulting forces exerted on the environment (Bertenthal & Clifton, 1998; Thelen, 2000). Finally, because motor behavior is both functionally relevant and directly observable, motor development makes an ideal model system for understanding change in other domains of development. Researchers can extrapolate from studies of motor development to other domains where the properties of interest are not so apparent, but the principles of change may be fundamentally the same (Adolph & Robinson, 2013; Dickinson et al., 2000).

Brain? Body? Both. More!

What drives motor behavior and its development? At first blush, the brain seems an obvious choice. The traditional approach to motor control assumes a central control system: the central nervous system (Schmidt & Lee, 2011). Likewise, the traditional approach to robotics and artificial intelligence assumes a primary driver: the algorithms in the software (Russell & Norvig, 2010). Indeed, the assumption of a central control system is so pervasive and the computer metaphor so powerful that researchers in motor control dubbed the neural representations "motor programs." But is it true? Is the central nervous system really in charge of motor behavior? Is the body that holds the brain or the hardware that houses the software irrelevant? And what of the environment in which the body moves? Wherein lies the control?

The details of the body and the environment necessarily affect motor behavior because the body is a physical system, subject to laws of physics, and always situated in an environment. The same muscle actions commanded by the central nervous system will result in very different movement outcomes depending on the size, weight, and composition of the limb, its current position relative to the body and to gravity, and inertial forces due to ongoing

movements (Bernstein, 1967). Conversely, achieving the same movement outcome can require very different muscle actions and thus different motor commands. To bring hand to face, an 8-week fetus must flex at the shoulder because the arm is so short; several weeks later, the same action requires flexion at the elbow because the arm is much longer (S. R. Robinson & Kleven, 2005).

The environment also constrains and supports motor behavior. Moving in the world entails continuous relations with gravity and friction, the media that contain our bodies, and the surfaces we stand on and touch. Vigorous leg kicks in a 10-week fetus can somersault it through the amniotic fluid (de Vries, Visser, & Precht, 1982). At 38 weeks, when the fetus is pressed against the uterine wall, the same kicks will not even extend the legs. After birth, without the buoyancy of a watery environment but with plenty of room to move, kicks do not propel the body but do extend the legs. The brain does not control the environment. Yet gravity, friction, surrounding media, and surfaces that exert force against our bodies are ubiquitous components of every motor action and contribute to movement outcome. Moreover, the world is filled with more than physical things. It is populated with autonomous agents—people and animals—who pose new constraints on and opportunities for motor behavior (von Hofsten, 2009).

In contrast to traditional movement science and artificial intelligence (AI), researchers in motor development have always recognized that the body plays a central role in motor behavior (McGraw, 1945; Shirley, 1931). Gesell (1939, 1946) explicitly drew on the work of the great embryologist, G. E. Coghill (1929), who viewed behavior and anatomy as inextricably linked. Indeed, the continuous change in infants' bodies is a salient feature of the classic motor milestone charts (Figure 4.1a). It is difficult to ignore infants' "hardware" given the rapid and dramatic changes in growth, body dimensions, and muscle tone over the fetal and infancy periods. The head is 50% of body length in the 8-week fetus, but only 25% in the newborn (Moore & Persaud, 1993). Newborns' predominant state of flexion gives way to a more equitable distribution of flexion and extension; the chubby 6-month-old becomes a slender toddler. Such changes are fast. Infants can grow 1.8 cm in length in a single day (Lampl, 1993) and head circumference can increase by 0.79 cm (Caino, Kelmansky, Adamo, & Lejarraga, 2010).

However, like traditional movement science and AI, the pioneers in motor development ignored the role of the environment. The infants depicted on milestone charts float on the white page with no ground to anchor them. Likewise,

the image gracing the title page of McGraw's (1945) classic text, *The Neuromuscular Maturation of the Human Infant*, is a tiny baby sitting in space (Figure 4.1b). The missing ground is no accident. In their zeal to extract infants' essential body parts and positions, early researchers extracted the baby from the environment. A more complete rendition of sitting is shown in Figure 4.1c. The infant is fully embedded in the physical and social environment and the caregiver and ground provide the infant with postural support.

A series of great insights brought brain, body, and environment together in the study of motor behavior. These insights distinguish modern approaches to motor development, movement science, and artificial intelligence from traditional ways of thinking. One insight is the lack of one-to-one correspondence between muscle actions and movement outcomes (Bernstein, 1967). Without such a correspondence, a complete description of motor behavior must include the role of body and environment in producing movement. No amount of computational power can supplant the passive forces exerted by the body and environment.

A related insight is the realization that the body and the environment need not be considered additional movement problems for the brain to solve. Rather the opposite: Some aspects of motor control can be outsourced to the body and the environment (Bernstein, 1967, 1996; J. J. Gibson, 1979; Pfeifer, Lungarella, & Iida, 2007; Pfeifer et al., 2012). Consider grasping a glass with the soft deformable tissue of the fingertips versus grasping with thimbles on each finger. Some of the problem of grasping is not solved by the brain but by the material and morphological properties of the hand relative to the glass (Pfeifer & Bongard, 2007). Consider walking over sloping ground. "Dynamic walking" robots have no software at all and no motors, but they can walk down slopes (Collins, Wisse, & Ruina, 2001). Like a slinky going down a staircase, the properties of their bodies, the slope of the ground, and gravity take care of the entire sequence of movements. And consider why infants walk at all. What prompts infants to take their first step? In many cases, it is the encouragement and helping hands of a caregiver.

A final most profound insight concerns development. In living creatures, body and environment naturally develop. A tiny embryo becomes a baby; the environment changes from womb to world. In principle, robots' bodies and effective environments also could develop, but as yet they do not (Pfeifer & Bongard, 2007). The insight is that processes of development can facilitate rather than hinder learning to control motor behavior (E. J. Gibson, 1988; Pfeifer, Iida, & Bongard, 2005; Stoytchev, 2009).

Whereas a robot can be programmed to assume a particular body and environment, babies cannot because yesterday's body or environment may no longer hold true today. This continual developmental flux discourages infants from learning particular motor solutions and encourages them to acquire flexibility and adaptability (Adolph, 2008).

These insights led to a modern developmental systems approach to motor development (E. J. Gibson & Pick, 2000; Thelen & Smith, 1994), dynamic systems (Kelso, 1995), and perception-action (J. J. Gibson, 1979) approaches to motor control, and a new field of developmental robotics (Lungarella, Metta, Pfeifer, & Sandini, 2003; Oudeyer, Baranes, & Kaplan, 2013; Vernon, von Hofsten, & Fadiga, 2011). The new approaches shifted emphasis from abstract, esoteric motor tasks to flexible, adaptive motor behaviors. The great challenges in artificial intelligence perhaps illustrate it best. In the 1950s, the great challenge was to design a computer program that could beat a chess grandmaster—a goal where all of the action was in the mind of the machine. In 1997, Deep Blue beat Garry Kasparov through sheer speed and scope of computation; commercial programs now can play world-class chess.

The same year that Deep Blue beat Kasparov, a new breed of AI researchers accepted a new great challenge, this one from the world of soccer: RoboCup. The ultimate goal is to build a team of 11 humanoid robots that can beat the human World Cup champion soccer team (Kitano, Asada, Kuniyoshi, Noda, & Osawa, 1997; Veloso & Stone, 2012; Visser & Burkhard, 2007). The robots must be autonomous agents, meaning no wizard behind a black curtain pulling the strings. Intelligent behavior in this case requires embodiment, but it requires much more. Like real soccer players, the robots must perform real-time reasoning and acquire strategies on the fly to engage in multiagent collaboration with players on their own team and cope with the changing strategies of the players on the other team. By 2006, RoboCup was the largest robotic event in the world. Perhaps in the not-so-distant future, developmental roboticists will build robots whose movements are truly embodied, embedded in a complex environment that poses variable and novel challenges, and enculturated to allow for interactions with other social agents. On that day, robots might run circles around the average 18-month-old.

EMBODIED MOVEMENT

Movements occur in a body, and the morphology of the body determines the range of possible movements.

Thus, developmental changes in body morphology change the possibilities for action. Jumping in grasshoppers provides a remarkable example of the developmental relations between body and movement (Queathem, 1991; Queathem & Full, 1995). If grasshoppers' growth were linear, we might expect a continuous upward developmental trajectory in jumping ability; but neither is the case. Grasshoppers jump farther when their exoskeleton is more rigid because part of their jumping power comes from releasing energy temporarily stored in the exoskeleton. However, while the exoskeleton is rigid, insects cannot grow. Juvenile grasshoppers and other arthropods must periodically molt—shed their exoskeleton—to increase in size. Between molts, grasshoppers double in mass, but the new soft exoskeleton is less able to store elastic energy and, as the exoskeleton hardens, the increase in muscle mass does not keep pace with the increase in overall body mass. The result is a scalloped developmental trajectory: Jumping distance doubles from juvenile to adult, but within each molt period, jumping distance begins low, increases sharply as the exoskeleton hardens, then decreases again because body grows faster than muscle.

Vertebrates have skeletons on the inside of the body and do not molt. But like growth in grasshoppers, human growth is not equivalent to simply scaling up the current form. Put a different way, infants are not Lilliputians with miniature adult bodies. Indeed, mere stretching would have disastrous outcomes. In *Gulliver's Travels*, Jonathan Swift simply scaled up the 60-foot Brobdingnagians relative to Gulliver's typical adult size, but these 90-ton giants could not have walked on dry land because, with Gulliver's dimensions, their bones would have broken under their great weight (Moog, 1948). Similarly, if a 2-meter-tall man falls, he will hit the ground with 20 to 100 times more kinetic energy than a toddler (Went, 1968). This is why toddlers can fall dozens of times per day with no untoward consequence (Adolph et al., 2012), whereas adults occasionally break a bone. Perhaps Haldane (1927) said it best: "To the mouse and any smaller animal, [gravity] presents practically no dangers. You can drop a mouse down a thousand-yard mine shaft; and, on arriving at the bottom, it gets a slight shock and walks away. . . . A rat is killed, a man is broken, a horse splashes" (p. 19).

Clearly, the body matters for motor behavior. This section on embodied movement focuses on general developmental issues regarding form and function while highlighting developmental relations between the body and motor outcome. We consider the developmental function of incidental activity, the problem of continuity between

earlier and later behavior, the role of variability in development, the treatment of time in developmental research, and the ways that children must adapt behavior to the short- and long-term status of their bodies.

Incidental Activity and Consequential Function

Motor behavior is ubiquitous. Movement begins as soon as fetal muscles are innervated. It occurs during waking and sleep. It happens incidentally as well as on purpose. And it includes actions not typically considered motor behavior—eating, speaking, and facial expressions (Green & Wilson, 2006; Nip, Green, & Marx, 2009; Wilson, Green, & Weismer, 2012).

Why so much movement and to what end? Some activities (breathing) support life and some activities (reaching) accomplish immediate goals. But even those activities that to casual observation appear to be random and purposeless—incidental by-products of some physiological process—may reveal exquisite real-time structure, change over development, and serve important developmental functions.

Moving Before Birth

Birth is not ground zero for behavior. Fetal movements appear at 5–6 weeks after conception (de Vries et al., 1982), shortly after nerves from the spinal cord establish functional synapses with muscle fibers. Fetuses in the first trimester—while still resembling a Kewpie doll with foreshortened limbs and a disproportionately large head—exhibit a variety of movements and postures (de Vries & Hopkins, 2005; Luchinger, Hadders-Algra, Colette, & de Vries, 2008): generalized movements that ripple through the entire body, sideways bending of head and trunk, startles, hiccups, twitches, isolated head, limb, and finger movements, “breathing” movements, “stepping” movements, somersaults, and facial movements such as mouth openings, tongue protrusions, and yawns. They bring hand to face and suck their fingers and thumb; they touch the umbilical cord and uterine wall (Sparling, van Tol, & Chescheir, 1999). They move freely through the amniotic fluid with their bodies oriented in every direction relative to gravity. By the second trimester, fetuses produce smiles, grimaces, and the distinct assemblage of facial movements that comprise adult-like expressions of laughter, crying, and pain (Azumendi & Kurjak, 2003; Reissland, Francis, & Mason, 2013; Reissland, Francis, Mason, & Lincoln, 2011). Hand-to-face contacts, kicks, hiccups, and other movements occur in bouts of activity

separated by 2- to 5-minute periods of quiescence (de Vries et al., 1982; de Vries, Visser, & Prechtel, 1985). Over development, body and limb movements generally increase in frequency—up to 30% of each day is spent actively moving—until the fetus’s growing body becomes cramped by lack of space; then movements decrease until birth (de Vries & Hopkins, 2005).

Why do fetuses move? Spontaneous motility is a product of the central nervous system. Thus, a primary motivation for studying fetal movements is to gain insight into the developing nervous system (S. R. Robinson & Kleven, 2005). An *in vitro* spinal cord, lacking both body and brain, generates spontaneous neural activity and patterned muscle activity when the nerves are attached to isolated muscles (Vinay, Pearstein, & Clarac, 2010). But fetal movements can reveal more sophisticated behaviors than a spinal cord in a dish. Fetuses open their mouths in anticipation of, not in reaction to, the hand arriving at the mouth (Myowa-Yamakoshi & Takeshita, 2006; Reissland, Francis, Aydin, Mason, & Schaal, 2014). On some level, the fetus must perceive that the hand is approaching the mouth and not another part of the face or head.

Moreover, causality can go in the other direction. The act of moving can influence the developing nervous system. A tiny flexible tether linking two legs together in a rat fetus changes the pattern of interlimb coordination from alternation, one leg at a time, to synchrony, two legs moving together (S. R. Robinson, Kleven, & Brumley, 2008). When the tether is cut and leg movements are again unconstrained, the new pattern of synchronous leg movements continues, indicating that real-time feedback from movement is detected and learned by the fetus. Thus, spontaneous movements generated by the fetal nervous system create sensory experiences that, in turn, generate neural activity that helps to shape neural development (Hepper, 2003).

Incidental fetal activity has other consequences for development, seemingly far afield. For example, moving before birth is necessary for proper physical development. Fetal movement exercises muscles, flexes joints, stretches skin, and circulates amniotic fluid. Without these consequences of movement, physical development does not proceed normally. Rat fetuses immobilized with curare do not develop normal facial features, skin, muscles, bones, connective tissue, mouth, gut, and lungs (Moessinger, 1983). The developmental functions of incidental activity span a variety of time frames. Some fetal movements are adaptations to life in the womb (e.g., swallowing amniotic fluid regulates water balance in utero and may stimulate

neural activity), some are preparation for birth (“version” turns the fetus into a cephalic head-down presentation for birth), and others presage functions for postnatal life (fetal “breathing” of amniotic fluid promotes normal lung development) and lay the groundwork for intentional action (fetal self-directed movements, such as hand-to-mouth, may be the earliest goal-directed actions). Indeed, most movements in the repertoire of the neonate have been practiced for months by the fetus (de Vries & Hopkins, 2005; Hepper, 2003).

Stereotypies and Flails

Spontaneous motility is a signature feature of infant movement. Over the first year, infants display a smorgasbord of kicks, stomps, sways, flaps, flails, rocks, rubs, nods, shakes, bounces, bangs, waves, and wiggles (Figure 4.2)—totaling 67 documented forms of movement of every body part, from tongue to toes (Piek & Carman, 1994; Thelen, 1979). Spontaneous movements occur in isolation (e.g., a single leg kick) and in bouts of rhythmic activity (e.g., repetitively flexing and extending the leg). They are frequent, up to several hundred movements per hour, and are frequently coordinated across the two sides of the body. Simultaneous kicks with both legs are more frequent than step-like alternation or single-leg kicks (Piek & Carman, 1994; Thelen, 1979); movements are more correlated between right and left arms and between right and left legs than between an arm and a leg (Kanemaru, Watanabe, & Taga, 2012); and an infant’s free hand is likely to produce spontaneous “overflow” movements while the other hand manipulates an object, sometimes exactly mirroring the rotating, shaking, and dropping movements of the object-oriented hand (Soska, Galeon, & Adolph, 2012).

What is the purpose of so much kicking, rocking, and waving? Flails, stereotypies, and overflow movements are more frequent when infants are mildly aroused, while engaged in social interactions, playing with toys, or fussing (Thelen, 1981), but they do not immediately accomplish anything. Spontaneous movements appear to be performed

for their own sake: When infants get excited, the nervous system produces movements. But this motility still can serve useful developmental functions. The same movements that infants display spontaneously can be harnessed for intentional action. For example, over the course of a few minutes, spontaneous kicks or arm flaps become seamlessly instrumental—what Piaget (1952) termed “secondary circular reactions”—when the previously inconsequential movements now cause an overhead mobile to jiggle (Thelen & Fisher, 1983). (Infants lay on their backs and limb movement is linked to the mobile by a tether or electronic sensor such that every kick or arm flap results in a satisfying jiggle of the mobile elements.) At first, infants increase movement in all their limbs (Kato, Watanabe, & Taga, 2013), but by 3–4 months of age, infants discern which limb is jiggling the mobile, they move the contingent limb more than noncontingent ones, and they remember the contingency for up to a week (Heathcock, Bhat, Lobo, & Galloway, 2005; Watanabe & Taga, 2006, 2011). Infants can even alter the form of their kicks if the contingency is specific to particular limb configurations (Angulo-Kinzler, Ulrich, & Thelen, 2002; Chen, Fetters, Holt, & Saltzman, 2002) or, if needed, kick with two legs instead of one (Thelen, 1994).

Thus, spontaneous motility ensures practice for many soon-to-be intentional movements and provides the raw material from which goal-directed actions are selected. Arm flapping and reaching provide another apt example. Months before they can bring their hand to a target, infants flap their arms when offered a toy. They also flap without the eliciting stimulus of a toy. Over several weeks, flaps gradually bring the hand closer to the toy and eventually result in consistent toy contact (Bhat & Galloway, 2006). As infants spontaneously flap with no toy, flap in the presence of a toy, and actually succeed in contacting the toy, many important aspects of goal-directed reaching improve simultaneously in all three contexts (H. M. Lee, Bhat, Scholz, & Galloway, 2008). For example, coordination at the shoulder and elbow becomes more adult-like,



Figure 4.2 Examples of spontaneous movements involving arms, legs, or torso in 6- to 12-month-old infants. From left to right: Alternate-leg kicking while supine, single-leg kicking while supine, arm-waving with object, lateral arm sway, sit-bouncing of the torso, hands-and-knees rocking, and bouncing while standing with support.

Source: Adapted from “Rhythmical Stereotypies in Normal Human Infants,” by E. Thelen, 1979, *Animal Behavior*, 27, pp. 699–715.

suggesting that the movements required for reaching are carved out from the spontaneous flaps.

Twitching During Sleep

We ordinarily think of sleep as the absence of behavior. But while fast asleep, mammals exhibit a peculiar type of involuntary motor behavior: twitching. Think of a sleeping dog twitching its nose, paws, and tail. The movements are brief, discrete, jerky, and isolated to one part of the body at a time. All of the skeletal muscles of the body twitch during sleep, and human infants sleep for 16 hours a day, adding up to hundreds of thousands of twitches (Blumberg, 2010).

Like fetal and neonatal movements, seemingly random twitches mask intricate temporal and spatial organization (Blumberg, Coleman, Gerth, & McMurray, 2013). In infant rats, twitches are dispersed in lightning quick 50-ms bouts nested within longer bouts lasting about 500 ms, which in turn are nested within bouts lasting 1–2 seconds. Twitches in one arm are followed by twitches in the matching muscle of the other arm: shoulder abduction on the left followed by shoulder abduction on the right, elbow flexion in one arm by elbow flexion in the other. Since the pattern occurs across the limbs in a girdle, the temporal links between joints cannot be the result of passive forces pulling the arm. And since the pattern evolves sequentially across limbs and muscles, it is not the result of simultaneous commands from a central controller.

Apparently, the brain takes notice. More frequent patterns of limb twitching in 2-day-old rats result in more organization in those patterns at 8 days of age; reciprocally, more organized patterns at 2 days result in more frequent expression of those patterns at 8 days (Blumberg et al., 2013). Twitches in the whiskers and limbs of infant rats trigger sensory feedback that drives activity in the brain and spinal cord (Tiriach, Ultermarkt, Fanning, Sokoloff, & Blumberg, 2013). So spontaneous activity of the sleeping nervous system generates twitches, which in turn relay information about the limb back to the developing nervous system. Infants may learn some of the most critical information about the workings of their bodies by moving while they are asleep.

Moreover, twitches during sleep are uniquely well suited for mapping muscle-to-brain relations because one muscle twitches while the others are completely quiet (Blumberg & Marques, 2013). Feedback from the twitch stands out against a background of atonic silence, like a bright light in a dark room. In contrast, waking movements in one part of the body typically are coordinated with other parts of the body within a context of postural compensations and

anticipatory postural adjustments. It is like trying to make yourself heard at a loud cocktail party.

Gross Motor Play

Children, like the young of other placental mammals, devote an inordinate amount of their waking lives to spontaneous, seemingly pointless, repetitive, voluntary activity—play (see Lillard, Chapter 11, this *Handbook*, this volume). Across species, gross motor play involves large movements of the body and appears in varied forms (see Burghardt, 2005, for examples below): exaggerated locomotion (e.g., foals gamboling), object-directed actions (kittens pawing a ball of yarn), and rough-and-tumble social play (young macaques slapping, biting, and chasing each other). Gross motor play typically involves modifications in form or timing compared to similar behavior in a functional context—think of the exaggerated jumps and bursts of speed in a puppy or young lamb. Movements are repeated, typically with novel variations. Social play often involves rapid role reversals, with the chaser becoming the chatee, and self-handicapping, as when an older juvenile monkey exercises restraint when play fighting with a younger sibling.

Play also is common among birds (crows repeatedly dropping and catching a stick in mid-air; parakeets ringing the bell in their cage) and is exhibited by reptiles (Komodo dragons pushing and shaking objects to make noise) and fish (leaping over turtles or floating objects). Even invertebrates, including insects, play: Captive octopuses grab floating objects, pull them down to the bottom of the tank, release them to watch the object shoot up to the surface; newly emerged worker honeybees engage in “play flight” by leaping into the air, flapping wings, drifting to the ground, then climbing up to repeat. Children’s gross motor play is comparable to these examples and more. They engage in spinning, rolling, handholding, and mock fighting; incorporate objects, surfaces, substances, and other people into their activities; and their play frequently involves sophisticated symbolic functions and rules (Burghardt, 2005).

Within and across species, playful activities do not reflect a common function or generative mechanism. The common thread is that they are voluntary, evidently pleasurable, and not immediately useful (Pellegrini & Smith, 2003). Although gross motor play has fascinated developmental and comparative psychologists for over a century, researchers still do not agree about how to define it, what it is good for, how it originated, or how it evolved (Burghardt, 2005). From an evolutionary perspective, play

poses a serious puzzle. In the wild and in captivity, play can take up to 20% of animals' time and 10% of their energy that otherwise could be channeled into growth (Fagen, 1981). Juveniles at play are conspicuous and less vigilant, exposing themselves to greater risk from predators and accidents. And play may depend on the availability of abundant nutrition and protective parents to create "surplus resources" that can be expended on "useless" behavior with little cost (Pellegrini, Dupuis, & Smith, 2007).

So why do young animals play? Play provides a source of physical activity that can promote development of bones and muscles (Pellegrini & Smith, 1998), a mechanism for generating variable neural activity and proprioceptive feedback to promote neural plasticity (van Praag, Shubert, Zhao, & Gage, 2005), opportunities to discover new skills (Spinka, Newberry, & Bekoff, 2001), and consequence-free practice for hazardous behaviors such as hunting and fighting (Fagen, 1981). Moreover, young animals reared without opportunities for normal social play show long-term deficits. Isolation-reared polecats are incompetent at mating and predatory killing (Eibl-Eibesfeldt, 1970) and rhesus monkeys reared in same-sex groups show aberrant sexual behavior as adults (Goldfoot, Wallen, Neff, McBair, & Goy, 1984).

Juvenile social play may even provide the basis for skilled performance under stressful conditions. When first encountering sunflower seeds, adult rats shred the shell, rendering the kernel inedible. After a few days, they learn to nip the ends and split the shell in half to remove the kernel. If reared with social play, rats easily open sunflower seeds in the presence of another rat, regardless of whether the interloper is dominant or subordinate. But subordinate adults reared in isolation revert to shredding in the presence of a dominant rat, suggesting that early social play provides the developmental basis for managing stress (S. M. Pellis & Pellis, 2009).

Developmental Continuity: Ontogenetic Adaptations, Historical Antecedents, and Primitives

Some behavior that appears early in infants' repertoire shares striking similarities with adult-like behavior. How shall we consider the relations between the two? One possibility is that the earlier appearing behavior has no direct relation to the later behavior; instead it is an ontogenetic adaptation, an alternative way of accomplishing a general function. A second possibility is that early and later appearing behaviors are related historically, but aspects of their form or function differ; the earlier behavior is a historical

antecedent. A third possibility is that the behaviors are identical; the earlier appearing behavior is a primitive that shares some critical feature of the later behavior.

Striking Similarities

A remarkable feature of some behaviors that appear early in development is their similarity to mature, adult-like behaviors. Fetal rats exhibit facial wiping behavior that bears striking resemblance to adult grooming: The animals bring one or both paws to their ears and stroke downward (Brumley & Robinson, 2004; Smotherman & Robinson, 1989). While still in the egg, chick embryos produce motions with their legs that—like a record spinning slowly beneath the needle on a turntable—turn the chick's body in a circle as the egg tooth cracks the shell for hatching. Once out, chicks use similar flexion and extension movements of their legs for walking (Bekoff, 1992). Newly hatched loggerhead sea turtles make their way into the ocean using the same trot-like crawling gait that they will exhibit years later when they return to nest on the beach of their birth, and the hatchlings swim away using the same "power stroke" gait—a sort of turtle breast stroke with front limbs sweeping backward simultaneously—that they will use for the rest of their aquatic lives (Wyneken, 1997).

Human infants also show an assortment of movements that foreshadow later ones: Fetuses and neonates bring hand to mouth using the same movements they will use months later for mouthing objects and eating (Sacrey, Karl, & Whishaw, 2012). Three- to five-month-olds spontaneously produce "vacuous" precision grips, bringing thumb to index finger with nothing in hand—the same movements that they will use months later to grasp a small object (Wallace & Whishaw, 2003). Banging a toy against the table at earlier ages uses the same up-and-down movements as hammering at later ages (Kahrs, Jung, & Lockman, 2012, 2013). Most celebrated are the "newborn reflexes"—sucking, palmar grasping, swimming (yes, underwater!), upright stepping, and so on—which bear striking resemblance to intentional sucking, grasping, swimming, and walking months later (McGraw, 1939; Zelazo & Weiss, 2006).

Relations Between Earlier and Later Behaviors

The similarities between earlier and later behaviors are indeed striking. But are the behaviors really the same? Movements at different points in development likely differ in details—banging in a toddler is less straight and controlled than hammering in an older child, just as hammering in a 3-year-old is less accurate and consistent than

hammering in an adult (Kahrs et al., 2012; Kahrs, Jung, & Lockman, 2014). However, exact replication is not the issue in considering developmental continuity. The issue concerns which aspects of the earlier and later behaviors are similar and how they are related developmentally (Adolph & Robinson, 2008).

Despite similarity in form or function, some earlier and later appearing behaviors are not developmentally continuous. The earlier behavior is merely a temporary solution for the problems facing the animal during a limited period of development. The placenta and umbilical cord provide an apt anatomical analogy of such an “ontogenetic adaptation” to a particular developmental niche (Oppenheim, 1980). Mammalian fetuses develop in the womb, where the placenta and umbilical cord transport all the necessary nutrients, fluids, oxygen, and other vital resources from mother to fetus and remove waste products in the other direction. These structures develop from embryonic (not maternal) tissues and serve essential physiological functions until birth. After birth they become afterbirth. The placenta and umbilical cord are no longer needed for ingestion and breathing and are discarded.

Suckling is another example of an ontogenetic adaptation that involves ingestion. Suckling, an essential activity expressed by all infant mammals, comprises a suite of behaviors that includes orienting toward the mother, finding and attaching the mouth to the nipple, rhythmic sucking which stimulates the mother to let down milk and extracts milk from the nipple, and finally disengaging from the nipple. Because the function of suckling is ingestion of nutrients and its form involves movements of the lips, tongue, and jaw, we might expect developmental continuity between suckling and feeding. However, suckling is not an early form of feeding. The sensory cues (odor and touch) to elicit suckling are qualitatively different from the factors that prompt feeding in adults (hunger and associations with particular foods and contexts). Moreover, adults stop eating when they are full, but infant rats continue to ingest milk as long as it is available (Hall & Williams, 1983). In some experiments, pups suckle until they are so filled with milk that they stop breathing. Even the patterns of muscle activation in the tongue and jaw differ when sucking a nipple versus eating or drinking (Steeve, Moore, Green, Reilly, & McMurtry, 2008; Westneat & Hall, 1992). Despite similarities in form and function (i.e., providing nutrition and fluids), suckling and feeding are distinct ingestive systems that develop independently, are controlled by different stimuli, and are regulated by different neural systems (Hall & Williams, 1983; Swithers, 2010).

In contrast to ontogenetic adaptations, earlier and later appearing behaviors can be related historically. The two behaviors can have different forms or functions, but the earlier behavior, like a movie prequel, lays the foundation for the later one. It is a historical antecedent. Embryology provides a clear analogy: The limb bud of a 4-week embryo is not yet an arm; it lacks bones, joints, and fingers. But it becomes an arm and is essential for the existence of the arm. The evidence is not merely circumstantial. Teratogenic drugs that disrupt the development of limb buds (e.g., thalidomide) result in malformation or complete absence of limbs (Ito et al., 2010). The earlier structure is necessary for development of the later structure.

Similarly, the clearest way to distinguish a typical precursor from a mandatory antecedent in behavioral development is to knock out the earlier behavior and observe whether the later behavior develops. For example, crawling typically precedes walking and babbling typically precedes speaking. However, despite the traditional lore that infants must crawl before they walk (see Figure 4.1a), some infants do not crawl and nonetheless walk normally (Adolph & Robinson, 2013). Crawling is not a true historical antecedent. In contrast, without the earlier period of babbling, infants do not learn to speak. If prelinguistic infants are prevented from producing vocal sounds due to the medical necessity of a tracheostomy, they do not produce communicative sounds once the tube is removed from their throat (Locke & Pearson, 1990). Babbling is not the same thing as speaking, but it is a necessary historical antecedent for speaking. The two behaviors are developmentally contingent.

A third conception of developmental continuity is an isomorphism between critical components of infant and adult behaviors. Early behaviors are “primitives,” “proto-somethings,” or forms of “core knowledge”; later behaviors are the mature endpoint. In fact, some researchers tackle the question of “what develops?” by assuming such isomorphic continuity unless proven otherwise: “...the null hypothesis in developmental psychology is that the cognitive mechanisms of children and adults are identical; hence it is a hypothesis that should not be rejected until the data leave us no other choice” (Pinker, 1996, p. 7).

In motor development, a popular candidate for a primitive is the alternating leg movements so characteristic of mature walking. Neonates and prelocomotor infants display alternating leg movements under a variety of conditions: while held in the air; supported on the ground; under water; facing forward, backward, and sideways on a treadmill moving at varied speeds; on a split-belt treadmill;

wearing weights on one leg; when one leg is pulled out from under them; and while viewing simulated optic flow (Barbu-Roth, Anderson, Despres, Provasi, & Campos, 2009; Barbu-Roth et al., 2014; Moerchen & Saeed, 2012; Thelen, Fisher, & Ridley-Johnson, 1984; Yang et al., 2004; Zelazo, Zelazo, & Kolb, 1972).

The developmental isomorphism between infant and adult leg movements also holds at a neural level. Despite different muscle actions for each type of alternating leg movement, the same neural circuitry that is responsible for forward, backward, and sideways treadmill stepping in newborns is operating during walking in adults (Dominici et al., 2011). Similarly, despite different muscle actions for different leg movements, the same neural circuitry produces leg movements during hatching and walking in chicks (Bekoff, 1992). And the same neural circuitry underlies trotting and swimming movements in turtles (Mui, Willis, Hao, & Berkowitz, 2012). Like the gears and axle in a car that produce forward and backward rotation by turning the wheels in different directions at different speeds, an identifiable system of neural circuitry can produce varied patterns of coordination in the legs.

So what are the developmental implications of striking similarities between earlier and later behaviors? Although some neural elements that will play key roles in adult walking can be active during newborn stepping, the two behaviors are not isomorphic. Newborns cannot support their own weight or keep balance without help. Successive steps are not consistently timed to ensure that one foot is always on the ground. And one foot may step while the other is passively dragged. Stepping is not walking.

The problem with the continuity assumption is that rejecting the null hypothesis is a matter of interpretation, not a matter of “the data leaving us no other choice.” For example, “cruising” (moving sideways in an upright position while holding onto furniture for support) is traditionally considered an early form of walking, although every researcher knows that cruising involves sideways not forward movement and infants do not support their full weight on their feet. Moreover, cruising serves the same general function as walking (upright locomotion), it is temporally contiguous with walking (infants cruise for several weeks before they walk), and it shares structural similarities with walking (upright, alternating legs). However, there is a critical functional discontinuity between cruising and walking: Experience cruising does not teach infants that they need a floor to support their body (Adolph, Berger, & Leo, 2011). In this sense, cruising does not prepare infants to walk and is not “proto-walking.”

Similarly, leg movements in the fetus may simultaneously be considered to have different continuity relations. Fetal leg movements may be an ontogenetic adaptation to the uterine environment that functions to orient the body or free the umbilical cord. Or they may be a historical antecedent that ultimately will allow moving in a gravitational environment. Or they may be a primitive that is continuous with adult walking. But there is no foolproof way to resolve the question of developmental continuity, because behavior, unlike anatomy, does not have a continuous existence. Any behavior is interrupted by other activities, including sleep, meaning that identical elements and functional relations are in the researcher’s mind, not in the data.

Variability: Problem and Promise

Like most areas of psychology, developmental research is typically geared toward assessing differences in average performance between groups or individuals. As a consequence, most developmental researchers consider intraindividual variability to be a nuisance, like variance in the error term of an ANOVA. Historically, research on motor development followed a different path. Change in intraindividual variability was always considered an important outcome and a window into developmental process (McGraw, 1935). Yet despite widespread appreciation that variability is a meaningful measure, researchers disagree about how to measure it and what it means (Deutsch & Newell, 2005; Dusing & Harbourne, 2010; Vereijken, 2010).

Consistency and Control

A basic fact of motor development is that motor skills become increasingly consistent, smooth, and precise with age and experience (Adolph & Berger, 2006; Bertenthal & Clifton, 1998). A common interpretation of this fact is that variability decreases as control increases. Variability in this sense is measured by quantifying the magnitude of variation around a central point. Infant reaching provides a good illustration: Intraindividual variability between reaches decreases, but what really characterizes improvement in infant reaching is a decrease in the variability of the movements *within* a reach.

Goal-directed reaching first appears at 11–24 weeks of age (Berthier & Keen, 2006; Clifton, Muir, Ashmead, & Clarkson, 1993; Konczak & Dichgans, 1997). The spread in onset age reflects the fact that getting a hand to a target is difficult. At first, infants reduce the number

of limb segments to control by cocontracting their elbow muscles to lock it in place; their reaches have inefficient, jerky, curved paths, with changes in course direction and multiple speed bursts (Berthier & Keen, 2006; Konczak & Dichgans, 1997; Spencer & Thelen, 2000; von Hofsten, 1991). After several weeks, elbow movement gets thrown back into the mix, allowing the hand to move on a straighter path to the target. Over the next 1–2 years, reaching gets smoother and more adult-like. Jerk (change in rate of acceleration) decreases; straightness (path relative to straight-line distance) increases; and changes in course direction decrease (Berthier & Keen, 2006; von Hofsten, 1991). Eventually, reaches coalesce into two adult-like phases: an early phase in which the hand rapidly accelerates toward the target, and a terminal phase in which the hand slows and adjusts for grasping before contacting the target (Konczak & Dichgans, 1997; Newman, Atkinson, & Braddick, 2001).

Learning to sit follows a similar developmental trajectory of improved proficiency and decreased intraindividual variability. The key to sitting is to control the segmented, eminently bendable, spinal column so that head and trunk stay securely inside the base of support provided by the baby's bottom and legs (Saavedra, van Donkelaar, & Woolacott, 2012). "Wobble" (variability in the location of spinal segments and the speed of trunk movements) and falling decrease as infants learn to anticipate and counteract effects of gravity on the head and torso.

Dynamic Stability

Linear measures of variability—as exemplified by jerk and wobble in infant reaching and sitting—do not reflect the sequence of values in a time series. Thus, based on linear measures, two very different time series, say a sine wave versus white noise, can have an identical magnitude of variation (e.g., the same range in values or the same standard deviation). In contrast, nonlinear measures of variability reflect the order of data points in a time series and are designed to reveal different underlying structures: A sine wave has a predictable, periodic structure whereas white noise has an unpredictable, random structure; and both signals show low mathematical complexity. Other time series such as "chaotic" attractors show intermediate levels of predictability and much more complexity compared to sine waves and white noise.

Thus, nonlinear measures of variability, such as approximate entropy (which quantifies predictability in the signal) and the Lyapunov exponent (which quantifies stable patterns and complexity in the signal), can reveal patterns of

change not revealed by standard linear methods (Stergiou, Yu, & Kyvelidou, 2013; Vereijken, 2010). Infants, for example, show greater predictability (smaller entropy values) and a compression of movement strategies (smaller Lyapunov values) as they acquire independent sitting, regardless of change in linear measures of variability (Dusing & Harbourne, 2010; Harbourne & Stergiou, 2003). Nonlinear measures also reveal structure in the variability of postural sway beyond infancy. Approximate entropy values show an inverted U shape in the variability of standing sway, increasing from 3 to 5 years of age (indicating less predictable sway) and decreasing from young to older adults (indicating more predictable, stereotyped sway). In contrast, linear measures of variability (total area traced by the center of pressure) yield a U-shaped progression in standing postural sway, with variability decreasing from 3 to 5 years of age and increasing from young to elderly adults (Newell, 1998). Opposite patterns in nonlinear and linear measures of sway suggest that postural development in childhood involves increasing control over more degrees of freedom (Hong, James, & Newell, 2008), which is then lost during aging (Newell, Vaillancourt, & Sosnoff, 2006).

A general conclusion from studies on dynamic stability is that too much variability leads to lack of stability and control, as in early stages of sitting and standing. But too little variability reflects inadequate complexity and fewer strategies for controlling posture, as in infants with developmental disorders and elderly adults. Nonlinear approaches thus suggest the Goldilocks Principle: Variability should not be too little or too much, but just right (Fetters, 2010).

Variation, Exploration, and Selection

"Just right" variability can support adaptation by providing the raw material for selection and refinement. Darwinian selection (propagation of successful variants, elimination of unsuccessful variants) can operate with reference to evolution, tuning of the nervous system, or behavior (McDowell, 2010; Sporns, 1997). In motor development, variability creates new forms that feed selective processes to make movements more adaptive (Hadders-Algra, 2000; Sporns & Edelman, 1993).

A selection process requires variants to act upon. When variation runs out, selection grinds to a halt. In evolution, new variants are replenished with each generation. In motor development, a renewable supply of variants arises through spontaneous activity and the practical impossibility of repeating actions in exactly the same way (Bernstein, 1967, 1996). We call it exploration and see it most clearly when infants face a novel task. When suspended for the first

time in a baby bouncer (a seat held by springs to the top of a doorway), infants have no idea how to behave, or even what the task is. Initially, spontaneous activity results in minimal bouncing, but this evokes more activity and—here is the crucial point—variable leg movements. Some jumps work against the natural periodicity of the springs, but some accentuate the bounce. Gradually infants converge on a solution in which the timing and magnitude of vertical jumps matches the stiffness and elasticity of the springs (Goldfield, Kay, & Warren, 1993).

A bouncing biped robot provides converging evidence of a variability-exploration-selection process (Berthouze & Goldfield, 2008). The robot was designed to produce a wide variety of variable jumps. Like infants, the robot initially generated small jumps in short, irregular bursts. As random jumping became more effective at producing a single bounce, the robot produced longer bouts of periodic jumping. Bouts that produced longer, stable periods of bouncing were selectively favored. Eventually the robot, like the infants, converged on behavior that matched the resonance of the spring system. Variation and selection among motor variants was sufficient to support motor learning.

Overlapping Waves and Variety of Means

Selection implies that less desirable strategies are eliminated from the motor repertoire. Similarly, stage theories of development imply that more advanced behaviors replace less advanced ones. An alternative possibility is that older, less optimal strategies coexist with newer, more optimal ones. On this view, development is like a series of overlapping waves. Existing strategies change in the frequency of expression, new strategies arise on the scene, and interactions among old and new strategies create more richness and variety of behavior (Siegler, 2006). In fact, using a variety of means to solve a problem may be a hallmark of adaptive behavior (E. J. Gibson & Pick, 2000; Piaget, 1952).

In cognitive development, strategy choice is generally adaptive. But children often discover new strategies despite successful performance with existing ones, they typically use a variety of means rather than only one strategy to solve a problem, and they often do not switch from old to new strategies even when new is clearly better (Schmuckler, 2013b; Siegler, 2005). Likewise, in motor development, infants generally select a locomotor strategy to suit the task. For example, toddlers walk down shallow slopes and slide down steep ones. But they discover new sliding strategies such as backing feet-first, despite already knowing how to slide headfirst and in a sitting position, and although any single sliding strategy would work, infants use all of them within a single session (Adolph, 1997). Infants persist in

using a variety of belly crawls and inchworm crawls despite inefficiency of particular movements (Adolph, Vereijken, & Denny, 1998; Patrick, Noah, & Yang, 2012), and less efficient movements coexist with more efficient ones for pulling to a stand (Atun-Einy, Berger, & Scher, 2012).

Likewise, in other animals, various movement strategies may emerge as overlapping waves. In rat pups, various righting responses (strategies for returning to a right-side up position if turned upside down) emerge at different points in development and change in frequency depending on the mélange of other movements in their repertoire, the availability of eliciting sensory information (e.g., pups are blind at birth), initial posture, and interactions between motor and sensory systems (V. C. Pellis, Pellis, & Teitelbaum, 1991). As a consequence, righting performance gets better, and then worse, then better again. It improves initially as newborns learn to bend into a U and flop to one side. Then corkscrewing dominates, with the shoulders turning one direction while the hips turn the other, like a body battling itself. Finally, the mature strategy emerges in which the head turns and the body follows.

The Passage of Time and Development

Behavior unfolds over multiple time scales, from milliseconds to millennia. Figure 4.3 illustrates the idea of multiple, nested time scales in walking: A single step occurs over the course of milliseconds, a sequence of steps over seconds, dramatic changes in sequences over months, and changes from infant to adult-like over years. Each time scale has its own trajectory, and in the case of walking, it has its own spatial trajectory as well.

Time as Maturation, Test Age, Onset Age, Experience

Developmental scientists are uniquely positioned to think about change over multiple, nested time scales, but we generally do a very poor job of it. Researchers in cognitive development typically consider “developmental time” in terms of chronological age and ignore other time scales (Siegler, 2006). This gambit is far worse than it sounds. Treating age as a predictor or independent variable confuses the passage of time with the factors actually responsible for creating developmental change; slotting children into age groups overlooks the fact that age groupings are transient and fictions of convenience (Wohlwill, 1970). Although motor development lends itself beautifully to deep analysis of time-based behaviors, research in this area is no better when it comes to analyses of developmental time (Adolph & Berger, 2006; Adolph et al., 2012). Like researchers in other areas, we typically put chronological age on the

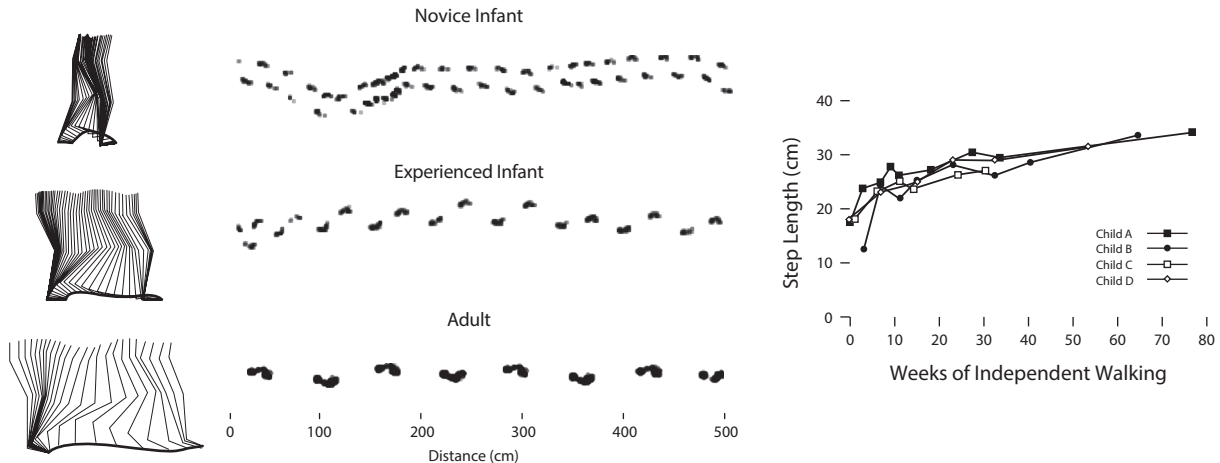


Figure 4.3 Developmental changes in walking in the standard “straight-line” paradigm over different time scales. The left column of stick figures depict the movement of the leg (gray line segments) and path of the foot (dark smooth line) during a single step in a 12-month-old novice walker (top), a toddler with 5 months of walking experience (middle), and an adult (bottom). Note that new walkers display exaggerated elevation of the foot relative to leg length and they drop the foot in place at the onset of stance, in contrast to the low trajectory of foot motion in adult walkers. The second column shows an example of footfalls during walking on a pressure-sensitive gait carpet, revealing the shorter, wider, more variable steps of an infant walker with only 2 weeks of walking experience (top), an infant with 2 months of walking experience (middle), and an adult (bottom). The graph at right shows the time course of improvement in step length (distance between consecutive steps) for four infants over the first 80 weeks of independent walking. Note the characteristic rapid increase during the first 10 weeks and slower, steady improvement over the subsequent 70 weeks.

Source: Stick figure data adapted from “Development of Independent Walking in Toddlers,” by Y. P. Ivanenko, N. Dominici, and F. Lacquaniti, 2007, *Exercise and Sports Sciences Reviews*, 35(2), pp. 67–73 and from “Kinematics in Newly Walking Toddlers Does Not Depend Upon Postural Stability,” by Y. P. Ivanenko, N. Dominici, G. Cappellini, and F. Lacquaniti, 2005, *Journal of Neurophysiology*, 94, pp. 754–763. Footprints adapted from “The Road to Walking: What Learning to Walk Tells Us about Development,” 2013, in P. Zelazo (Ed.), *The Oxford Handbook of Developmental Psychology* (pp. 403–443), New York, NY: Oxford University Press. Step length data from “Head Coordination as a Means to Assist Sensory Integration in Learning to Walk,” by B. Bril and A. Ledebt, 1998, *Neuroscience and Biobehavioral Reviews*, 22, pp. 555–563.

x -axis (e.g., Berthier & Keen, 2006; Kahrs et al., 2012). Maturation, always a popular explanatory principle in motor development (e.g., Dominici et al., 2011), represents only time passing and has no explanatory value beyond neural-hand waving as an agent of change. Onset age, a long-favored measure in motor development, represents only the number of days between birth and the first appearance of a motor behavior (e.g., Saavedra et al., 2012). Experience performing the skill is no better. As normally indexed, experience is only the number of days between onset and test dates (Adolph, Vereijken, & Shrout, 2003); essentially, we replace chronological age on the x -axis with “walking age” or “sitting age.”

The development of walking is a good example of behavioral descriptions at different ages, in this case, different *walking ages*. In the standard test, infants are encouraged to walk repeatedly over a straight, flat path. After a century of increasingly sophisticated recording technologies, what have we learned from the standard test? To the naked eye, infants’ first steps look wobbly, choppy, unbalanced, and idiosyncratic; after a few months, walking looks relatively smooth, rapid, stable, and uniform. Recordings from gait

carpets, force plates, high-speed motion trackers, and electromyography confirm these impressions (Adolph & Robinson, 2013; Lacquaniti, Ivanenko, & Zago, 2012; Sutherland, 1997). Simply put, walking improves.

New walkers suffer from poor balance control (Halleman, De Clercq, & Aerts, 2006). Their initially slow, asymmetrical, short, wide steps become faster, more symmetrical, longer, and narrower, and they spend less time with both feet on the ground (Chang, Kubo, Buzzi, & Ulrich, 2006; Ledebt, van Wieringen, & Savelsbergh, 2004). Abrupt flat-footed or toe-first landings transition into cushioned heel-toe landings and toe-off progression (Halleman et al., 2006). Some new walkers hold their arms up like balance poles, creating variable forces on the trunk; over several weeks, their arms lower and eventually swing (Corbetta & Bojczyk, 2002; Kubo & Ulrich, 2006). New walkers’ knees and hips are flexed in the stance leg, causing the torso to lean forward; the hip is elevated as the leg swings forward, so the pelvis tilts from side to side. The overall consequence is inefficiency. Relatively little kinetic energy from forward movement is recaptured as potential energy (Halleman, Aerts, Otten, De Deyn,

& De Clercq, 2004; Ivanenko et al., 2004; Kimura & Yaguramaki, 2009; Kimura et al., 2005). As knee and hip become more extended in stance, the pelvis stays level, the torso is more erect, and more of the energy expended in forward movement is recovered (Holt, Saltzman, Ho, Kubo, & Ulrich, 2006). New walkers show more cocontraction of their leg muscles and poorly timed bursts of muscle activity (Chang et al., 2006). Over ensuing weeks, the idiosyncrasies of new walkers transform into more uniform solutions (Bonneuil & Bril, 2012; Snapp-Childs & Corbetta, 2009). Across measures, the rate of improvement is initially rapid over the first 4–6 months of walking and then slows over the next several years (Adolph et al., 2003; Ivanenko, Dominici, Cappellini, & Lacquaniti, 2005; Ledebt, Bril, & Breniere, 1998).

Despite the elegant technologies and gorgeous descriptions of change within steps and across sequences, research on infant walking is still lacking fundamental information about developmental time. After all these years, we still put walking age on the x -axis and call it “experience.” But *what do infants experience* during natural walking? The actual facts are astounding yet obvious. Each hour, infants spontaneously take 2,300 steps, travel the length of 8 football fields, and fall 17 times; over the course of a waking day, toddlers accumulate over 14,000 steps, travel the length of 45 football fields, and fall 100 times (Adolph et al., 2012). They do not do this, however, by traipsing back and forth in straight lines as in the standard walking task. They turn! Natural walking is omnidirectional. Infants’ paths meander wildly (Figure 4.4) and half of their walking bouts have only one to three steps—too short for standard gait analyses. Human infants are not unique in this. For all animals at every point in development, steady straight locomotion is the exception, not the rule (Dickinson et al., 2000; Kramer & McLaughlin, 2001; Orendurff, Schoen, Bernatz, Segal, & Klute, 2008). In fact, training robots to walk like infants—with omnidirectional gait on variable paths instead of periodic gait in straight lines—was sufficient to win all 24 games in the 2011 RoboCup, scoring 136 goals and conceding none (MacAlpine, Barrett, Urieli, Vu, & Stone, 2012). Other teams have now caught on: The actual experiences matter, not the empty passage of time.

Sampling and Stages

Ironically, with so much time on the x -axis, developmental research has few guidelines for how to space observations over time. Generally, sampling intervals are quite large. In cross-sectional studies, we compare newborns, toddlers, preschoolers, and adults (Dominici et al., 2011).

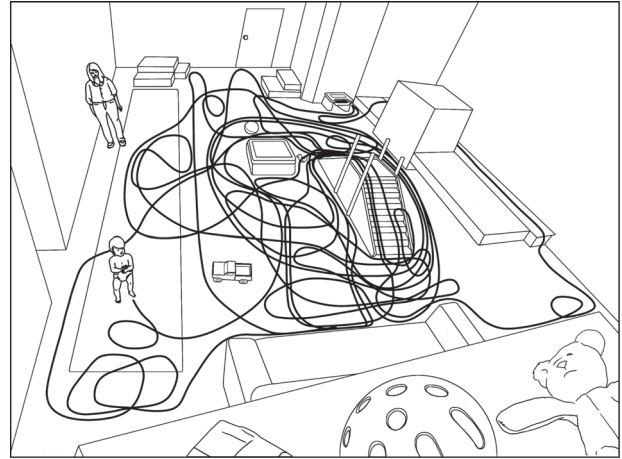


Figure 4.4 Natural infant walking in a large laboratory playroom containing a long gait carpet (left), couch (bottom), padded pedestal, slide and stairs, narrow catwalk, carpeted and wooden steps, an activity table, and a wall lined with shelves of toys. The superimposed line shows the walking path of one typical 13-month-old during 10 minutes of spontaneous activity.

Source: From “How Do You Learn to Walk? Thousands of Steps and Hundreds of Falls per Day,” by K. Adolph et al., 2012, *Psychological Science*, 23, pp. 1387–1394. Adapted with permission.

In longitudinal studies, we observe infants at walking onset and 3 months later (Chang et al., 2006). Under more heroic regimes, we test infants weekly or monthly (Hallemans et al., 2006). Such decisions about sampling intervals are based on tradition, convenience, or intuition. But, overly large sampling intervals compromise our ability to discern the true shape of the developmental trajectory (Adolph & Robinson, 2011).

For example, the standard growth charts showing smooth, continuous increase in children’s height derive from quarterly or yearly measurements (Kuczumski et al., 2002). Daily measurements reveal that growth is actually episodic, with dramatic spurts within a single day followed by no growth for days or weeks (Caino et al., 2010; Lampl, Veldhuis, & Johnson, 1992). The same problem holds for binary data such as infants’ ability to walk, produce words, or demonstrate object permanence. The widespread practice of attributing an onset age to the first appearance of a skill relies on the assumption that skill acquisition is stage-like—before this day, infants cannot walk; after this day, they can. Daily sampling, however, reveals variable trajectories. Most motor skills sputter in and out of infants’ repertoires—they walk on one day, but not again until a few days later. Infants can exhibit dozens of vacillations between “pass and fail” before the skill stabilizes (Adolph, Robinson, Young, & Gill-Alvarez, 2008). Simulations of sampling at different rates (every other day, every third

day, every fourth day, and so on) show that the ability to detect a variable trajectory decreases precipitously with each day of widening the sampling interval. With weekly samples, half of the variable skill onsets appear stage-like; at a monthly sampling rate, nearly all variable skill onsets appear stage-like. Infrequent sampling can mistake the date of first appearance by weeks—a virtual lifetime in infant motor development. Regardless, first appearance is an arbitrary choice given variable patterns of onset.

What, then, is the take-home message from so much depressing news about the (mal)treatment of time in developmental science? Developmental research has the tools and concepts for describing and explaining change over time. We just need to do it.

Adaptation and Developmental Diversity

Behavior is movement of the body. Changing the body experimentally or during everyday activity alters the real-time biomechanical constraints on movement. Similarly, developmental changes in the body alter the biomechanics of movement. With normal physical growth comes increases in overall body size and also changes in body proportions (Adolph & Avolio, 2000; Bogin & Varela-Silva, 2010; Carrier, 1996). Thus, learning to move entails learning to adapt behavior to short-term changes in the body, and acquiring new motor skills entails learning to move in your particular body.

Coordinated movement is a continual dialogue between body and brain. Consider the celebrated case of the Hensel twins, conjoined mid-thorax. Each sister's brain controls the limbs on one side of the body in continual dialogue with her sister's brain so that the girls learned to clap their hands, walk, bicycle, play basketball, swim, drive, and most other typical bilateral skills. The central nervous system cannot contain motor programs—either hardwired or learned—to control the necessary body parts for movement because it cannot know the relevant body specifications ahead of time. Without foreknowledge of the “hardware specs,” the central nervous system cannot generate the appropriate muscle forces to move the appropriate body parts. Addressing this “calibration problem” (S. R. Robinson & Kleven, 2005) is one of the central challenges in developmental science. Nonetheless, researchers have scarcely begun to examine the changing relations between the growing body and motor development.

Short-Term Effects of Changing Biomechanics

A simple way to experimentally manipulate body dimensions is to add weight to the body. An external load, like a

backpack, adds mass and shifts the location of the center of mass; this requires modifications in posture and gait to solve the new balance problem. Older children and adults adjust smoothly, leaning away from the load to maintain their center of mass over the base of support (Brackley, Stevenson, & Selinger, 2009). Adults also adapt to loads on the limbs. Adding weights to the thighs, shanks, or ankles increases the energy cost of walking, but does not cause significant gait disruptions (Browning, Modica, Kram, & Goswami, 2007). Infant walkers alter arm position while carrying objects (Mangalindan, Schmuckler, & Li, 2014), but paradoxically they do not compensate for packs on their backs, fronts, or sides. They lean into the load, allowing their center of mass to creep dangerously close to the edge of the base of support. Infants also fall more frequently while carrying loads, despite strategies to improve balance such as shorter, wider steps, slower speeds, and longer periods with both feet on the ground (Garciguire, Adolph, & ShROUT, 2007; Vereijken, Pedersen, & Storksen, 2009).

Another way to experimentally manipulate body dimensions is to alter limb lengths. For example, leg length was ingeniously altered in Saharan desert ants by clipping the distal segment of the leg (“stumps”) or gluing a bristle to the end of the leg (“stilts”). The altered ants moved their legs as before such that stilt steps were 14% longer and stump steps were 33% shorter than normal ant steps. Because changes in leg length systematically altered step length, stilts traveled greater distances and stumps shorter distances in the same number of steps, resulting in systematic navigation errors (Wittlinger, Wehner, & Wolf, 2006). In contrast to ants, children with artificially elongated legs do not immediately move their legs as before. Boys walking on stilts and a boy with achondroplastic dwarfism after surgical lengthening of his lower legs shortened their steps and reduced their walking speed, presumably to cope with the new balance constraints of their unfamiliar, longer legs (Dominici et al., 2008).

Long-Term Adaptation to Body Changes

People come in all shapes and sizes, and for motor control, size matters. Atypical bodies are common in sport performance. The average height of players in the National Basketball Association is > 2 meters (79 in.); the average weight of a lineman in the National Football League is 142 kg (313 lbs.); the average height and weight of an Olympic female gymnast is 1.5 m (61 in.), 47 kg (103 lbs.). However, researchers know surprisingly little about motor skill acquisition in people with such atypical body morphology.

Atypical bodies are also common in everyday life: Overweight and obesity are epidemic among American children—in fact, so prevalent that overweight may soon become the norm (Ogden, Carroll, Kit, & Flegal, 2012). Overweight and obesity are associated with decreased motor coordination in childhood and delayed development in infants (Graf et al., 2004; Slining, Adair, Goldman, Borja, & Bentley, 2010). Obese children walk with shorter, wider steps, at slower speeds, and spend more time supported by both feet and less time supported by just one foot (Dufek et al., 2012; Hung, Gill, & Meredith, 2013; Wearing, Henning, Byrne, Steele, & Hills, 2006). Differences in the timing of hip and knee muscle activation result in longer stance, greater lateral movement of the leg during swing, and reduced extension of the hip.

As one would predict from moving heavier legs, widening stance, and reducing the pendular efficiency of swinging the legs, energy utilization is less efficient and the mechanical cost of locomotion is greater for obese children (Nantel, Brochu, & Prince, 2006). However, the increase in energy expended during walking (about 10%–25% more per kilogram in obese adults) is less than one might expect—much less, for instance, than the 80% increase experienced by a lean person wearing external leg weights walking in a similar pattern (Browning & Kram, 2009). This counterintuitive fact implies that obese children and adults adapt to their bodies by walking in a more energy-efficient manner. One possible explanation is that obese people expend more energy moving heavy legs, but less energy supporting their weight on straight knees (DeVita & Hortobagyi, 2003). Reciprocally, massive (33%) weight loss results in reduced time in stance, longer and narrower steps, increased preferred walking speed, greater range of hip motion, and greater knee flexion—effects that reflect the opposite adaptation as obesity gives way to a leaner body (Hortobagyi, Herring, Pories, Rider, & DeVita, 2011).

The effects of growing up with different body dimensions are particularly evident when expanding the range of human variation (Blumberg, 2009). Achondroplastic dwarfism, for instance, alters bone growth and results in short stature with short arms and legs relative to the trunk and head (Wynne-Davies, Walsh, & Gormley, 1981). Although this condition does not directly affect the nervous system, it results in motor delays (Fowler, Glinski, Reiser, Horton, & Pauli, 1997; Ireland et al., 2010). Infants sit at 12 months (compared to 6 in typical infants) and walk at 18 months (compared to 12). Locomotor development includes unusual behaviors such as “log-rolling” and

“snow-plowing” on legs and head. Because their arms are about the same length as their legs, achondroplastic infants crawl on hands and feet instead of hands and knees. Due to hypermobility at knees and hips, achondroplastic infants transition from crawling or lying to sitting by pushing themselves straight back through a “straddle split” so they are facing their original orientation. Typically developing infants, in contrast, roll one hip over the ipsilateral leg, turning the body 90° away from the original direction of crawling (Soska, Robinson, & Adolph, in press). Both methods appear biomechanically favored for infants’ respective body proportions. Developmental plasticity ensures that children who grow up with atypical bodies can produce adaptive motor behaviors.

Summary: Movement Is Embodied

Most research on motor development is of the embodied type—studies of infants’ movements that implicitly acknowledge the body in the form of the measurements (limb trajectories, forces, muscle actions, etc.) or explicitly examine the effects of the body on motor outcomes (e.g., obesity). The literature shares a deeper theme of embodiment, however. These are studies of the morphology of movement—its form and shape—and the evolution of behavioral morphology over space and time. As Gesell (1946) wrote in a previous chapter of this *Handbook*, motor behaviors “have shape” (p. 297). In fact, the early pioneers represented infants’ bodies in isolation (Figure 4.1a–b) so as to highlight the changing morphology—the body, so to speak—of infants’ movements.

EMBEDDED ACTION

Animals are always situated in a physical environment that constrains, shapes, and invites motor action. Some factors are omnipresent—gravity, temperature, air, and ground. But most environmental factors are continually in flux—the layout and the objects and surfaces therein. All of it affects motor development. Rats reared in microgravity on a space shuttle do not show surface righting and never achieve normal righting responses back on earth (Walton, Harding, Ansel, Harris, & Llinas, 2005). If the room is too hot or too cold, sleeping rat pups do not twitch normally and awake movements also differ in hot and cold (Blumberg, 2001).

The variable nature of the environment requires that actions be flexible and adaptive. Even a simple creature like the worm *C. elegans* (302 neurons) adapts to the

environment by swimming in water and crawling on land (Pierce-Shimomura et al., 2008). More sophisticated animals rely on perceptual information to guide actions adaptively. Perception does not just happen to a passive perceiver, like a patron waiting for the server to arrive with a meal. Instead, we do things to make perception happen; we sample and select from a buffet of potential information. Perception does not occur only in the brain; it is a whole body activity. Animals generate perceptual information through action (J. J. Gibson, 1979; Noe, 2004). Human vision is a clear example. Although the fovea is very small, we have an illusion of seeing equally well over the entire visual field because we turn our eyes and head to where our attention is directed (von Hofsten, 2013). In the language of the new robotics, animals “self-structure” perceptual information (Pfeifer, Lungarella, Sporns, & Kuniyoshi, 2007).

This section on embedded action highlights the developmental interplay between goal-directed action and exploration of the environment—learning to act on and interact with the physical world. The focus is on perception-action development and how infants learn to cope with novelty and variability in the environment. We describe how infants extract information from the environment by exploring from a distance and through direct contact, how this information is used to plan actions in advance and during execution of a skill, and how children learn the limits of their motor abilities in specific situations.

Learning by Doing: Exploration of the Environment

From the very beginning, infants are motivated to explore the environment and all that it affords for action (von Hofsten, 2009, 2013). Motor development—postural control, mobility, and manual dexterity—initially limits access to the environment and then expands the effective environment (E. J. Gibson, 1988). In this sense, infants’ environments, like their bodies and skills, develop. No body part is universally privileged for exploration. Animals have evolved different anatomical and sensory solutions for exploring the environment from a distance and for getting to know it up close. What all exploratory systems have in common is an active search for information that involves putting the right body part in the right place and moving it.

Exploration From a Distance

For humans, vision is a primary means of exploring the world from a distance (see Johnson & Hannon, Chapter 3, this *Handbook*, this volume). Until recently, research on infants’ visual exploration of the layout relied on

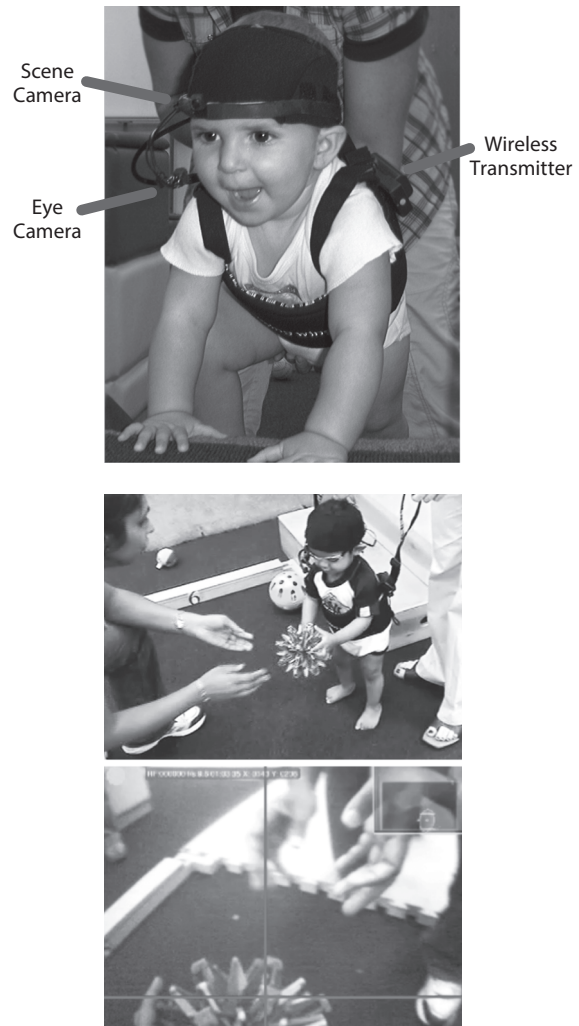


Figure 4.5 Head-mounted eye-tracker worn by a 14-month-old infant (top), objective camera view of the activity of the infant in the laboratory playroom (middle), and child’s view and point of gaze, shown by crosshairs, provided by the head-mounted scene camera (bottom). The small inset in the top right of the bottom photo shows picture-in-picture from the eye camera.

Source: Adapted from “Head-Mounted Eye Tracking: A New Method to Describe Infant Looking,” by J. M. Franchak, K. S. Kretch, K. C. Soska, and K. E. Adolph, 2011, *Child Development*, 85, pp. 278–293.

third-person camera views and intuition. A popular (and eminently reasonable) idea was that locomotion and visual exploration are developmentally related: Spying a distant object gives infants incentive to move and seeing obstacles a few steps ahead spurs gait modifications and changes in path (E. J. Gibson & Schmuckler, 1989; Piaget, 1954). Now researchers can measure visual exploration directly with head cameras and head-mounted eye trackers (Figure 4.5).

In the natural environment, adults and infants look at an object just before their hand moves to reach for it

(Franchak et al., 2011; Hayhoe & Ballard, 2005). While walking, adults, children, and toddlers direct gaze mostly at objects they are moving toward, not at obstacles in the path. Obstacle fixations are always brief and are more frequent in toddlers (72% of obstacle encounters) than in children (59%) or adults (32%). Otherwise, navigation is guided by information from the periphery (Franchak & Adolph, 2010; Franchak et al., 2011). One reason for the developmental shift from foveal to peripheral control is differences in eye height: Shorter observers naturally see more of the ground near their feet.

Postural development constrains looking in other ways. While prone or crawling, infants mostly see the floor; while supine they see the ceiling; but when infants sit or stand up, the whole room swoops into view (Kretch, Franchak, & Adolph, 2014). What do they look at? Freely mobile infants look surprisingly little at faces, which are typically too high, and infants seldom tilt their heads up (Aslin, 2009; Franchak et al., 2011). As Frank, Simmons, Yurovsky, and Pusiol (2013) put it, toddlers “spend much of their time in a world primarily populated by knees” (p. 454). Even while sitting across the table from each other, mothers typically look at their infants, but infants rarely look at their mothers (L. B. Smith, Yu, & Pereira, 2011). Mothers see infants’ faces and the whole tabletop. Infants see mostly objects and hands.

Although visual exploration dominates the research on exploration, other perceptual systems can serve as long-distance probes. Owls use sound to find a scampering mouse in the dark. Rat dams find lost pups from ultrasonic cries. Salmon smell their way upstream to the place they were spawned. Fish use pressure-sensitive pits along their bodies to detect vibrations produced by other fish. Whales navigate by listening to breakers crashing against a distant shore. Pigeons and sea turtles orient by detecting Earth’s magnetic field. Bats and dolphins echolocate by bouncing sound from their cries off objects. Electric eels and fish electrolocate by generating electrical fields that are distorted by the bodies of other fish. In all cases, perception guides locomotion via information generated, reflected, or distorted by distant features of the environment.

Exploration Through Direct Contact

Information from a distance can prompt exploration by direct contact (Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Adolph & Robinson, 2013). Sight of an obstacle in the path—albeit in mostly brief, incidental glances from the periphery—prompts infants to pause at the edge of the obstacle and probe its surface with hands or

feet. Some ground properties are emergent—friction and rigidity—and *must* be explored through direct contact. Infants explore the slip of their shoes against a sloping surface by rocking their feet at the brink (Adolph, Joh, & Eppler, 2010; Adolph, Karasik, & Tamis-LeMonda, 2010a). They explore the compliance of a waterbed or foam pit by pressing their hands into the surface (E. J. Gibson et al., 1987; Joh & Adolph, 2006). Over weeks of crawling and walking, exploration becomes faster, more efficient, and supports more error-free navigation.

Likewise for objects: The sight or sound of a nearby object prompts prehension and manual exploration. Sighted infants reach for objects sounding in the dark (Clifton, Rochat, Litovsky, & Perris, 1991) and blind infants reach for continually sounding objects (Ihsen, Troester, & Brambring, 2010). Some object characteristics are revealed only through touch—texture, rigidity, weight, and temperature. At first, infants use mouth, lips, and tongue to explore objects (Rochat, 1983). Then, as posture improves and infants can sit up, hands predominate and eventually work in tandem with mouthing and visual inspection (Ruff, Saltarelli, Capozzoli, & Dubiner, 1992; Soska & Adolph, 2014).

On one view, haptic perception piggybacks on developments in manual dexterity. Some exploratory procedures identified in adults (lateral finger motions to discover texture, contour following to reveal shape, etc.) are too difficult for very young infants, so haptic perception suffers (Bushnell & Boudreau, 1998). However, simple exploratory procedures are available early. By 3 months of age, infants differentiate object weight based on unsupported holding (Striano & Bushnell, 2005) and by 4–6 months they differentiate object rigidity based on squeezing and tapping (Morange-Majoux, 2011). Between 6 and 10 months, infants explore object-surface relations differently by pressing a spongy cube but banging a rigid one (Bourgeois, Khawar, Neal, & Lockman, 2005). By 3 years of age, children show the full adult-like repertoire of exploratory procedures (Kalagher & Jones, 2011) and by 4 years they exhibit adult-like procedures to explore the rigidity of a mixing stick (Klatzky, Lederman, & Mankinen, 2005). On a second view, adult-like exploratory procedures are unnecessary. Newborns exhibit rhythmic changes in finger pressure that yield information about object texture, shape, and weight long before more complex manual actions are available (Molina & Jouen, 2004).

Mouths and hands are not the only way to “feel out” the environment, especially for animals. Whisking is an example. At birth, rats’ whiskers are sensitive to touch, but

movement is largely passive. Over the next three weeks as pups develop postural and locomotor skills, their whiskers fan out, sweep to and fro in waves, and move individually like fingers to explore the layout (Grant, Mitchinson, & Prescott, 2012). Whiskers are like fingers in another sense. Each whisker has its own representation in somatosensory cortex. If a whisker is clipped, barrel fields in somatosensory cortex reorganize; ditto as the whisker grows back (Erzurumlu, 2010).

Planning and Innovating: Prospective Control

In a variable world, actions must be planned and prospective (J. J. Gibson, 1979). Children must lift their foot to avoid tripping on an obstacle (Franchak et al., 2011) and lower their foot to go down stairs (Cowie, Atkinson, & Braddick, 2010); turn their bodies to steer through narrow openings (Franchak & Adolph, 2012) or circumvent an obstacle in the path (Vallis & McFadyen, 2005); retract their heads to dodge a looming object (Schmuckler, Collimore, & Dannemiller, 2007); move their hand to catch a ball (Kayed & Van der Meer, 2009; van Hof, van der Kamp, & Savelsbergh, 2008); and avoid getting hit by a car when crossing the road (Grechkin, Chihak, Cremer, Kearney, & Plumert, 2013; te Velde, van der Kamp, Barela, & Savelsbergh, 2005). Actions must be selected, timed, and shaped prospectively to adapt to the changing environment.

Infants show evidence of prospective control from the start. Fetal mouth opening in anticipation of the thumb may be the first inkling of prospective control (Reissland, Francis, Aydin, et al., 2014). The fact that 10-month-olds adjust their reach depending on whether they intend to throw a ball into a tub or push it down a tube provides exquisite evidence of prospective control (Claxton, Keen, & McCarty, 2003). Similarly, older infants alter the speed of their initial reach for a block depending on whether the block is placed on a tower or thrown into a tub (Chen, Keen, Rosander, & von Hofsten, 2010). Preschoolers plan their initial step onto a target so that their next step lands on a nearby target, like using stepping-stones to cross a river (Cowie, Smith, & Braddick, 2010). Prospective control improves with age and experience by bringing action into closer alignment with what children intend to do and what the situation requires. For example, 4- to 11-year-olds show age-related refinements in reaching depending on subsequent demands for precision after grasping the object—holding the object, fitting it into a tight hole, placing it in a loose hole, or tossing it into a bin (Wilmot, Byrne, & Barnett, 2013).

Intuitively, prospective control may seem simple. It is not. We are used to thinking about time in terms of dichotomies: prospective-reactive, feedforward-feedback. But time runs irreversibly in one direction. What has just happened is *only* relevant for what will come next (von Hofsten, 2009, 2013). Actions are always prospective, just more or less accurate, more or less sensitive to current constraints, more or less attuned to the animal's goals, and planned more or less far into the future. In biological systems, the delays in neural control pathways may be substantial—greater than 200 ms for visual-motor control in adults and longer for infants. Waiting for feedback is not always viable. Imagine the delay waiting for feedback from sensor to brain to muscle in a blue whale. It is more adaptive to adopt a succession of motor control strategies: formulate a plan before acting, modify ongoing movements as needed, and discover new means on the fly.

Formulate a Plan

For an old-fashioned industrial robot to grasp an object, it brings the “hand” to the right location, stops, swivels the effector into the correct orientation, adjusts the aperture of its “grip,” and then clamps on. But this clunky, discrete sequencing works only for grasping the same objects in the same location and only for transport actions that can be halted mid-stream. No bird stops mid-flight to open its feet to perch on a branch, no shark stops mid-pursuit to open its mouth to bite its prey, and no person stops mid-reach to spread the fingers to grasp. It is all one fluid motion. In the course of moving their hand to an object, adults form a grip based on its intended use and visual information about its size, shape, and orientation; transport and grasp are flexibly integrated and geared prospectively to object properties.

Although infants exhibit visually guided grasping by 4 months, coordination between transport and grip formation is not fully adult-like until 12 years of age (Smyth, Katamba, & Peacock, 2004; Vollmer & Forssberg, 2009). At first, infants' hands are closed into fists at object contact. Then they reach with the hand wide open and adjust their grip after object contact. Then the fingers begin to close during transport in anticipation of grasping the object. Eventually, infants use visual information to conform thumb-finger grip aperture and hand orientation to object properties—smooth balls and fluffy pompoms, straight and tilted rods, regular and irregular shaped objects—even when the object translates or rotates (Barrett, Traupman, & Needham, 2008; Fagard, 2000; von Hofsten & Johansson, 2009; Witherington, 2005). Adjusting grip aperture and hand orientation simultaneously is more difficult than

dealing with only one dimension, but infants solve this by 12 months of age (Schum, Jovanovic, & Schwarzer, 2011).

Generally, infants preshape the hand for a power grip (all fingers wrap around the object), but for tiny objects or toys with protuberances, they switch to a precision grip with thumb and forefinger (Barrett et al., 2008; Fagard & Lockman, 2005; Newell, McDonald, & Baillargeon, 1993; Newell, Scully, McDonald, & Baillargeon, 1989). Between 5 and 13 months, reaching with one hand for small objects and two hands for large objects becomes more reliable (Fagard, 2000; M. H. Lee, Liu, & Newell, 2006); infants scale the space between their two hands to object size (van Wermeskerken, van der Kamp, & Savelsbergh, 2011); and they aim their two hands closer to the center of mass of an irregularly shaped object (Barrett & Needham, 2008). By 3 years of age, children switch from one- to two-handed grasping when object size exceeds finger-thumb aperture size (Huang, Ellis, Wagenaar, & Fetters, 2013).

Sometimes prospective control of grasping stretches farther into the future than simply preparing the fingers to latch on. The intended use may require an initially awkward grasp so that subsequent movements are comfortable and efficient—dubbed the “end-state comfort” effect (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). Adults, for example, grasp an object to be inverted with the thumb awkwardly pointing down so that the grip is comfortable when the object is rotated; you flip an upside down glass before filling it with water (Figure 4.6a–b). Prospective control in this case entails a second step that is not immediately accessible to visual guidance. Transport and grip formation are still in play for the initial grasp, but planning for the end state determines whether to grasp thumb up or down, over- or underhand.

Do infants exhibit two-step action planning? At 9–14 months of age, infants grasp a spoon laid horizontally with their preferred (right) hand. When the handle points right, they use an overhand, power grip and bring spoon to mouth

with the thumb near the bowl (Claxton, McCarty, & Keen, 2009; McCarty, Clifton, & Collard, 1999, 2001; McCarty & Keen, 2005). They do exactly the same thing, however, when the handle points left, only now the overhand power grip causes them to bring spoon to mouth with the pinky finger near the bowl—an unwieldy end state that causes the food to spill. At 19–24 months of age, infants use the same overhand grip, but when the handle points left, they use their left hand to grasp and the food arrives intact. The same grip strategies hold for other tools such as hammers (Figure 4.6c–e). Is this evidence of two-step planning? Yes, but infants switch hands rather than switch grips, presumably with some cost for manual control in the second part of the action sequence. By 4 years of age, children show the first evidence of adult-like end-state planning, sometimes using their dominant hand with an *underhand* power grip, thus bringing spoon to mouth with the thumb near the bowl (Keen, Lee, & Adolph, 2014). By 8 years, awkward pinky-to-bowl grips have completely disappeared and children primarily use underhand power grips or adult-like fingertip grips with the dominant hand (Figure 4.6f–g).

Hand choice can show stronger evidence of end-state planning when the tool-target relation requires bringing the hand toward the chest. Two-year-olds grasp a stick laid horizontally with their preferred (right) hand to sweep a toy toward a goal on either side of the table, whereas 3-year-olds grasp with the hand opposite the goal to make the sweeping motion more comfortable and efficient (Cox & Smitsman, 2006). However, 2-year-olds can select the grasping hand with the end state in mind when raking rather than sweeping the object (Rat-Fischer, O’Regan, & Fagard, 2012b).

Two-step planning of manual actions is clearly more difficult when only the preferred hand is allowed (Jovanovic & Schwarzer, 2011), and children do not consistently display end-state planning with their dominant hand until 10–12 years of age (Rosenbaum et al., 2012). Thus, children

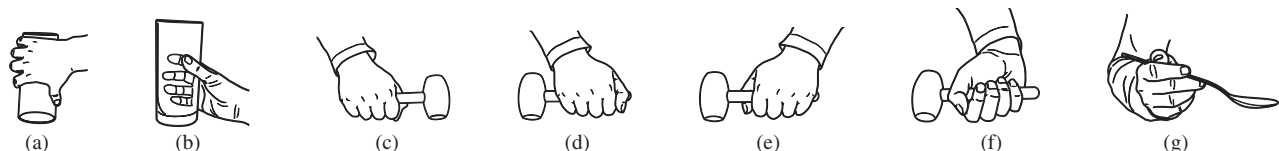


Figure 4.6 Various grip configurations for grasping a tool with one hand. (a) Side view of initial grasp of upside-down glass with power grip of right hand, thumb down. (b) End state grip of glass right-side up with right hand, thumb up. (c–f) Overhead views of initial grasps of the handle of a hammer. (c) Adult-like overhand grip with preferred (right) hand using hammer, thumb to working end. (d) Inappropriate overhand grip with right hand, pinky to working end. (e) Overhand grip with nonpreferred (left) hand, thumb to working end. (f) “End-state comfort” underhand grip with right hand, thumb to working end. When the wrist rotates, the hammer will be in the most comfortable and efficient position to pound a peg. (g) Adult-like precision grip with fingertips of right hand holding a spoon.

would make lousy waiters: Four- to 6-year-olds show end-state comfort when inverting a water glass on fewer than 50% of trials (Adalbjornsson, Fischman, & Rudisill, 2008; L. E. Robinson & Fischman, 2013). They would also make lousy fencers: Ten-year-olds display end-state planning when grasping a sword on only 61% of trials (Craje, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010; Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Craje, & Steenbergen, 2013). Adult monkeys are about on par with children: Rhesus monkeys use whichever hand allows for a thumb-to-bowl overhand power grip on a spoon (E. L. Nelson, Berthier, Metevier, & Novak, 2011). Tamarins invert a cup using a thumb down grip on 83% of trials (Weiss, Wark, & Rosenbaum, 2007). Lemurs use the thumb down grip on 38% of trials (Chapman, Wiess, & Rosenbaum, 2010).

Is the cognitive dimension (representing the end state and sequencing of actions) what makes two-step planning with the dominant hand so hard? Perhaps it is not so hard. One difference between children and adults is consistency of grip choice. Many children show the end-state effect only on a subset of trials whereas adults show it on every trial. Consistency may have more to do with task compliance and cost assessment than children's ability to form a plan (Wunsch, Henning, Aschersleben, & Weigelt, 2013).

Modify the Plan

Once the hand is positioned on the object, it is a simple matter to grasp. Or is it? Robots designed with traditional notions of action feedback are notoriously poor at grasping. Too little pressure causes the robot hand to drop the coffee cup; too much pressure crushes it (Pfeifer & Bongard, 2007). Think of picking a ripe raspberry. Grip force should be just above the level needed to keep the object from slipping out of the fingers. To lift an object by grasping requires coordinating the grip forces used to squeeze the object between the fingers and the load forces used to lift the object off the table. Adjusting grip to object compliance, weight, and slip requires continual modifications of the action plan, as these properties cannot be seen in advance like object shape. They must be felt—at least on the first encounter. Online modification of finger forces and position requires rapid tactile feedback from the object and efficient activation of finger muscles.

Development of control over finger forces for grasping (squeeze and lift) takes years. Protracted development is less about strength and more about coordination. Long before infants show visually guided grasping, they close

their fingers around an object placed in their hand. But the grip forces are typically excessive. Neonates can grasp an experimenter's fingers so tightly that the experimenter can lift them from the examining table. Likewise, newborn monkeys can cling so tightly to their mothers' fur that they can hang on as mothers walk and climb. In Halverson's (1931) words, "Infants from birth to 6 months exhibit a grasp of a force entirely disproportionate with the pressure necessary to hold and lift the seized object. Whether the object be heavy or light, it is driven hard against the palm in a vice-like palm grip, which is purely an expediency for procuring and holding the object" (p. 258).

At 2–3 months of age, infants' index and middle fingers exert most of the grip force (Lantz, Melen, & Forssberg, 1996). Between 4 and 7 months, power grip forces increase (Sgandurra et al., 2012). When picking up a narrow object, infants grip first (sometimes generating negative load force by pushing down) and then lift upward; the grip force is excessive for preventing slip, even when lifting an object covered with sandpaper, not slippery silk (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991). Over the next few years, children show increasing coordination between grip and load forces until their timing and amplitude are smoothly coordinated. Moreover, from infancy to adulthood, children show improvements in their ability to learn over trials about the appropriate forces for lifting objects varying in slip, weight, and size, and show faster, more appropriate responses to unexpected perturbations, as when the experimenter drops a weight onto the object midlift (Vollmer & Forssberg, 2009).

A "spring" task yields an elegant model of rapid online adjustment. When holding a spring between index finger and thumb, exerting more force in the fingers compresses the coils of the spring, but also causes the spring to become more unstable. To keep the spring from buckling while maintaining tight compression requires the fingers to exert faster and faster tiny adjustments. Children's manual dexterity continually improves in this task between 4 and 16 years of age (Dayanidhi, Hedberg, Valero-Cuevas, & Forssberg, 2013), alongside age-related decreases in muscle contraction time (Dayanidhi, Kutch, & Valero-Cuevas, 2013), increases in motor speed (Gasser, Rousson, Caffisch, & Jenni, 2010), and improvements in tactile spatial resolution (Bleyenheuft, Wilmotte, & Thonard, 2010). Manual dexterity, muscle contraction time, motor speed, and tactile spatial resolution depend on cortical sensory and motor mechanisms that are not adult-like until 12–18 years of age or later (Fietzek et al., 2000). Thus, online modification of precision grip develops gradually

over nearly two decades as experience with objects and neural control of finger musculature work hand-in-hand.

Make a New Plan

Sometimes the original plan is unworkable or there is no ready-made plan. Flexibility—the ability to transfer existing means to a new situation or to concoct a new plan—is a cornerstone of adaptive behavior (E. J. Gibson & Pick, 2000). True motor skill involves problem solving and creativity (Connolly & Dalglish, 1989). Improvisation and innovation are key. Lack of flexibility is a primary impediment in designing freewheeling, adaptive robots. Current robots cannot use old strategies in new ways or discover new solutions on the fly (Pfeifer et al., 2005; Stoytchev, 2009).

Infants, in contrast, repurpose old movement strategies, recombine existing skills in new ways, and invent utterly new solutions. For example, the short, wide immature steps of the novice walker enjoy new life as adaptive gait modifications in experienced toddlers and adults—to brake forward momentum while walking down slopes (Gill, Adolph, & Vereijken, 2009) or to keep balance on the rolling deck of a ship (Stoffregen, Chen, Yu, & Villard, 2009). Crawling infants recombine existing strategies to carry objects: They crawl while holding objects in their mouth or pushing them on the floor; they bum-shuffle while holding the object in hand or under an arm (Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2012). Walking infants, like adult hikers crossing a log over a stream, revert to crawling to cross a deformable waterbed or squishy foam pit (E. J. Gibson et al., 1987; Joh & Adolph, 2006). When toddlers face a slope too steep to manage by braking, long discarded forms of belly crawling and bum shuffling reappear as descent strategies to slide down headfirst or in a sitting position (Adolph, 1997).

Examples of strategy discovery abound: Infants “cruise” over a low handrail by hunching over at their waist or cruising on their knees instead of feet (Berger, Chan, & Adolph, 2013). Infants turn around (detouring) and back feet-first to descend pedestals, drop-offs, stairs, and steep slopes (Adolph, 1997; Berger, Theuring, & Adolph, 2007; Kretch & Adolph, 2013a). McGraw’s (1935) description of how infants acquire the backing strategy to descend 70-inch pedestals without banging their chins or crashing at the bottom still makes for a gripping read. Moreover, detouring adds challenging cognitive demands for infant humans and other animals (Lockman & Adams, 2001; B. P. Smith & Litchfield, 2010). The backing strategy, including the detour, emerges in various ways: constructed out of whole

cloth, discovered serendipitously in the course of doing something else, piecemeal, or all at once (Adolph, 1997; McGraw, 1935).

Tool use is emblematic of strategic planning and innovation. In tool use, infants use an object or part of the environment as a means to augment their body capabilities to attain a goal. For example, toddlers use handrails to augment their balance while climbing stairs or crossing bridges; moreover, they distinguish the utility of the handrail based on its distance from the bridge and whether it is composed of sturdy wood or wobbly rubber (Berger & Adolph, 2003; Berger, Adolph, & Kavookjian, 2010; Berger, Adolph, & Lobo, 2005). Like Köhler’s (1925) chimps, toddlers rearrange the environment to create new means by relocating or stacking boxes to reach lures hanging from the ceiling (McGraw, 1935). However, the most sensible solutions, such as stacking boxes smaller upon larger, emerge only after weeks of practice.

Handheld tool use is considered the epitome of flexibility and problem solving, perhaps because innovation, manufacture, and use of stone tools was a turning point in human evolution (Shumaker, Walkup, & Beck, 2011). Children’s play with objects seems to entail limitless variety of manual, creative actions. But making tools is not child’s play (Beck, Apperly, Chappell, Guthrie, & Cutting, 2011). When a tool must be invented, manufactured, or used for a particular (adult-defined) purpose, young children show protracted development and many limitations in planning the actions (Chappell, Cutting, Apperly, & Beck, 2013). Three- to 7-year-olds, for example, bend and straighten a pipe cleaner during play, and they choose a bent pipe cleaner to hook an out-of-reach object. But they do not spontaneously bend the pipe cleaner to use as a hook without prior demonstration (Beck et al., 2011; Cutting, Apperly, & Beck, 2011).

Of course, the motor components of manual tool use are important (Lockman, 2000; Smitsman & Bongers, 2003). Infants’ first adult tool, the spoon, requires a host of skills to load the spoon with food and transport it to mouth: unimanual grips, hand position on the handle, spoon angle positions to keep the bowl upright, arm positions while loading and transporting, anticipatory mouth opening, visual monitoring, and inhibition of movements in the other hand (Connolly & Dalglish, 1989; Gesell & Ilg, 1937). The process is still incomplete by 2 years of age. However, problem solving and innovating new plans requires something more cognitive. The familiarity of the spoon leads to “functional fixity”; toddlers are loath to treat the handle as the business end even when the bowl

is clearly unsuitable (Barrett, Davis, & Needham, 2007). Three-year-olds persevere by pulling a cane toward an object that needs pushing if they did the pulling motions first (Smitsman & Cox, 2008). Two-year-olds fail to use a rake if the target sits slightly outside the protruding edge of the tool (Rat-Fischer, O'Regan, & Fagard, 2012a). Perhaps most astounding, 1- to 3-year-olds make scale errors by trying to use a doll-sized tool on a person-sized object and vice versa (Casler, Eshleman, Greene, & Terziyan, 2011). The grips are appropriate, two-step planning is evident, but children bring the wrong tools to the job.

Tool manufacture and use is widespread throughout the animal kingdom, from bug to bird, fish to octopus, rat to elephant, and monkey to ape (Shumaker et al., 2011). But two species rise above the rest as flexible and effective tool makers/tool users in the wild, chimpanzees and New Caledonian crows (McGrew, 2013). Chimps strip a slender branch to use as a "fishing lure" for termites or ants. They often begin by using a stouter stick to break a hole in the nest and then delicately insert the probe into the tunnel to extract insects clutching onto the twig (Shumaker et al., 2011). Chimps may bite the end of the probe to create a frayed, brush tip better able to secure insects (Sanz, Call, & Morgan, 2009). Crows fabricate equally elaborate tools by carefully crafting hooks at the end of stripped-down twigs or by fashioning probes by cutting the barbed leaves of pandanus trees into slender shapes (Hunt & Gray, 2004a, 2004b). The probes then are inserted into crevices to prize grubs.

Chimps attend to functional properties of food extractors. For example, they choose longer sticks to retrieve rewards from deeper tubes (Sabbatini et al., 2012). Crows likewise recognize the functional properties of stick tools. When presented with a hooked stick with a nonfunctional end, crows grasp the tool in their beak so as to hold the hooked-end downward. If the tool is presented upside-down, the crow flips it (Holzhaider, Hunt, Campbell, & Gray, 2008) or even inverts its head 180° to grasp it in the functional direction, consistent with end-state comfort (St. Clair & Rutz, 2013). Thus, both chimps and crows adopt successive strategies when facing motor challenges. They both preshape their grip to grasp a tool (Formulate a Plan). They modify tools as needed by reducing the length, trimming parts, or fine-tuning the business end of the tool (Modify the Plan). They also alter the means-ends relations by flipping a stick to reverse its orientation, dropping or manipulating it to change grips, exchanging it for another tool, or abandoning the stick to manufacture an entirely new tool (Make a New Plan).

Learning the nuances of making, using, modifying, and switching tools takes a long time. Young chimps require up to 2 years to become proficient at selecting and using stones as hammers to smash nuts against an anvil stone (Inoue-Nakamura & Matsuzawa, 1997). Juvenile crows require more than a year to achieve adult levels of grub fishing (Holzhaider, Hunt, & Gray, 2010). Moreover, tools are manufactured following consistent, detailed procedures that are standardized in a local area (Hunt, 2000; Hunt, Corballis, & Gray, 2006; Nishie, 2011; Sanz et al., 2009). Although neither chimp nor crow parents actively teach offspring about tool manufacture and use, infant chimps and juvenile crows spend much of their time hanging out with skilled adults and gaining access to discarded tools (Holzhaider et al., 2010; Inoue-Nakamura & Matsuzawa, 1997). In this regard, they are very like human children that grow up in a material culture (Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009).

Perceiving and Generalizing: Affordances for Action

Selecting (or guiding, modifying, or creating) actions from the set of all possible actions presupposes that animals can tell which actions are possible and which are not. Distinguishing possible from impossible actions is what J. J. Gibson (1979) termed "perceiving affordances." An affordance is the fit between an animal's capabilities and features of the environment that make a particular action possible (Franchak & Adolph, 2014a). A drop-off is navigable if the obstacle is suitably small relative to the animal's leg length, limb strength, and balance control. An aperture is passable if the opening is sufficiently large relative to the size, deformability, and slip of the body parts. Actions are possible or not, regardless of whether the affordance is perceived. But perceiving affordances is what we must do for actions to be prospective and adaptive.

The affordance concept is inherently comparative and profoundly developmental (Adolph, Eppler, & Gibson, 1993; E. J. Gibson & Pick, 2000). The distinction between possible and impossible drop-offs is meaningless for animals that walk down vertical walls (e.g., geckos, houseflies). Passable aperture size means something entirely different to an animal with a skeleton than to an octopus. Different species have different bodies, skills, ecological niches, and life tasks, and so different affordances for action. For every animal, affordances develop. What is impossible earlier in development can become possible later, and vice versa. For children, developmental changes are rapid and dramatic. A crawler last week is a walker this

week. A poor walker this week will be better next week. Physical growth and new postural, locomotor, and manual skills expand the effective environment and invite new opportunities to take advantage of what the environment affords. Learning to perceive affordances happens concurrently with the development of new affordance relations. Learning occurs in the context of continual development.

Learning in Development

Learning in the context of development has two important implications. One implication concerns information overload. Only a subset of possible actions is relevant for the task at hand and only part of the available information is relevant for perceiving those affordances (E. J. Gibson & Pick, 2000). Animals never use all the information reaching their receptors; they never perceive every option for action. Instead, animals sample from this vast pool so that only some of the potential information for affordances becomes effective.

Earlier periods of development create a smaller set of action possibilities than later periods, thereby reducing the maelstrom of perceptual information for affordances. Fetuses can perform innumerable actions, but the set of affordance relations between fetal body and uterine environment is smaller than the set of relations between toddlers' bodies and their environments, which in turn is smaller than that of adolescents. In this sense, immaturity of infants' perceptual-motor systems is an advantage because it effectively decreases information overload, and thereby constrains learning (Lungarella et al., 2003; Stoytchev, 2009). As learning progresses, so does development. Infants are born with the perceptual-motor skills they practiced prenatally, which now can be used to discover new affordances in the more complex extrauterine environment. Bootstrapping between learning and development continues throughout the lifespan.

The second implication concerns flexibility. Learning in the midst of development results in learning that is sufficiently flexible to scale up to the novelty and variability that characterize everyday activity in the natural environment. A compendium of fixed solutions (or for robots, preprogrammed routines) is not viable long-term because yesterday's solution may no longer work with today's body and environment (Adolph & Robinson, 2013; Stoytchev, 2009). Infants do not really learn to move. Instead, infants acquire something like learning sets; to use Harlow's (1949) phrase, they are "learning to learn" to move. They learn to generate and detect information for affordances at each moment—what they can do right now with this body

and these skills in this environment for this task (Adolph, 2008). The flux of a changing body in a variable world ensures that infants learn to perceive affordance relations (my current leg length and level of balance control relative to the features of that particular drop-off) rather than static facts (big drop-offs are dangerous, or my balance is shaky).

As in acquiring simple learning sets (Harlow, 1949), learning to learn entails immense amounts of variable experiences over a very long time. But this presents no real limitation for motor development. By 3.5 months of age, infants have performed 3–6 million eye movements (Johnson, Amso, & Slemmer, 2003); at 11–13 months, they spend half of each waking hour interacting with objects (Karasik, Tamis-LeMonda, & Adolph, 2011); at 12–19 months, they take 14,000 steps per day (Adolph et al., 2012).

Development also puts limits on the flexibility of learning. New action systems create entirely new affordance relations. Thus, learning to perceive affordance relations does not transfer from one perception-action system to another (Adolph, 2008). Why should it? Affordance relations for crawling and walking, for example, are completely different. Exploratory movements to generate information for affordances are different. Thus, crawling experience teaches infants to perceive affordances for crawling; walking experience provides opportunities for learning about affordances for walking.

Variations in the Environment

For many animals, the size of a drop-off affects affordances for locomotion. In the classic "visual cliff" paradigm (Figure 4.7a), animals approach an apparent drop-off on a glass-covered precipice (Adolph & Kretch, 2012; Adolph, Kretch, & LoBue, 2014; E. J. Gibson & Walk, 1960). When they first learn to crawl, human infants (and other animals that do not locomote at birth) cross right over the safety glass; avoidance requires several weeks of self-produced locomotor experience (Campos, Bertenthal, & Kermoian, 1992; Held & Hein, 1963; Witherington, Campos, Anderson, Lejeune, & Seah, 2005). Experience is also necessary in paradigms where the information for the drop-off is veridical. On real cliffs, gaps, slopes, bridges, and ledges (Figure 4.7b–f), novice crawlers and walkers repeatedly fall over the brink of impossibly large drop-offs, whereas experienced infants precisely scale attempts to cross to the affordance relations (Adolph, 1997, 2000; Franchak & Adolph, 2012; Kretch & Adolph, 2013a, 2013b). (No worries: An experimenter rescues infants when they fall.)

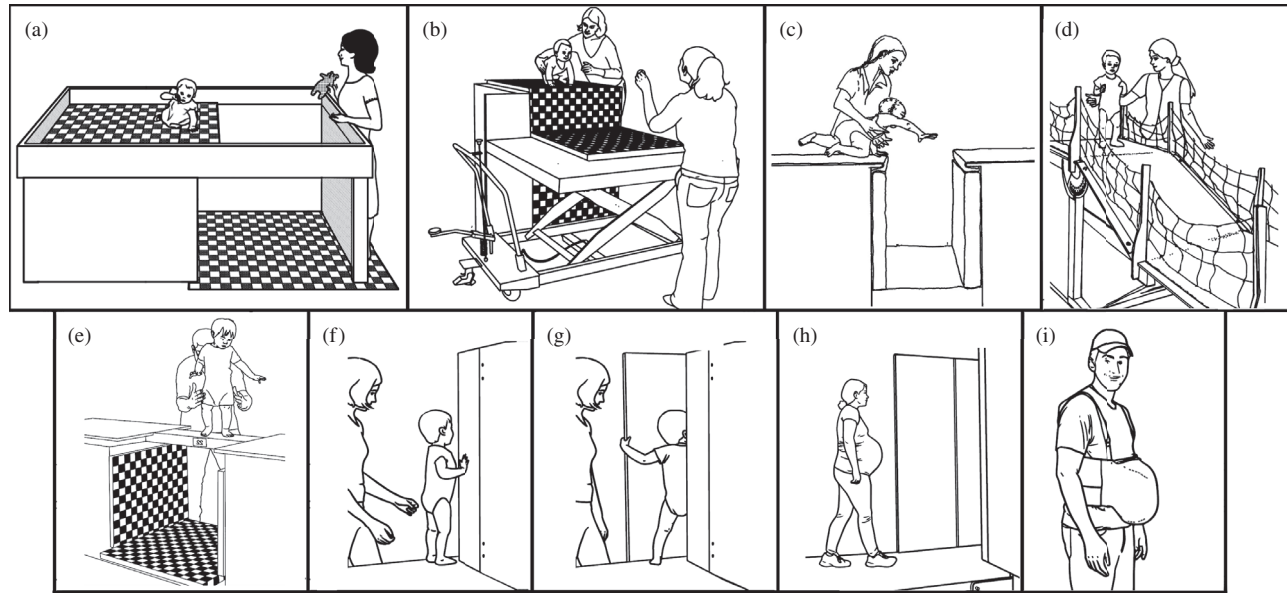


Figure 4.7 Various apparatuses used to test infants' perception of affordances as they encounter novel and variable challenges to balance and locomotion. (a) Crawling infant facing a visual cliff. The surface on the deep side is 102 cm below the edge. (b) Crawling infant facing a real cliff, with an adjustable drop-off of 0–90 cm. (c) Crawling infant facing a gap (0–90 cm) in a horizontal walkway. (d) Toddler preparing to descend an adjustable slope (0°–90°). (e) Toddler crossing a bridge over a gap. The width of the bridge adjusts from 2 to 60 cm. (f) Toddler negotiating a narrow ledge above a cliff. The ledge width adjusts from 0 to 70 cm. (g) Toddler squeezing through an aperture (0–70 cm) between vertical walls. (h) Adult pregnant woman preparing to walk through a narrow aperture. (i) Adult man wearing a “pregnancy pack” before testing with a narrow aperture. In each of the experiments involving infants (a–f), an experimenter followed alongside infants to ensure their safety. Caregivers (shown only in a and b) encouraged infants from the far side of the obstacle.

Source: Adapted from “Specificity of Learning: Why Infants Fall Over a Veritable Cliff,” by K. E. Adolph, 2000, *Psychological Science*, 11, 290–295; “Infants’ Perception of Affordances of Slopes under High and Low Friction Conditions,” by K. E. Adolph, A. S. Joh, and M. A. Eppler, 2010, *Journal of Experimental Psychology: Human Perception and Performance*, 36, pp. 797–811; “Infants on the Edge: Beyond the Visual Cliff,” by K. E. Adolph and K. S. Kretch, in *Developmental Psychology: Revisiting the Classic Studies*, edited by A. Slater and P. Quinn, 2012, pp. 35–55, London, England: Sage; “What Infants Know and What They Do: Perceiving Possibilities for Walking through Openings,” by J. M. Franchak and K. E. Adolph, 2012, *Developmental Psychology*, 48, pp. 1254–1261; “Gut Estimates: Pregnant Women Adapt to Changing Possibilities for Squeezing through Doorways,” by J. M. Franchak and K. E. Adolph, 2014, *Attention, Perception, and Psychophysics*, 76, pp. 460–472; “Cliff or Stop? Posture-Specific Learning at the Edge of a Drop-Off,” by K. S. Kretch and K. E. Adolph, 2013, *Child Development*, 84, pp. 226–240; and “No Bridge Too High: Infants Decide Whether to Cross Based on Bridge Width Not Drop-Off Height,” by K. S. Kretch and K. E. Adolph, 2013, *Developmental Science*, 16, pp. 336–351.

Is this evidence of learning to learn or learning something else? A popular interpretation is that locomotor experience teaches infants a general rule: fear of heights (Campos et al., 1992; Witherington et al., 2005). In line with this view, infants show accelerated heart rate, an index of fear, if placed on the glass covering the deep side of the visual cliff (Ueno, Uchiyama, Campos, Dahl, & Anderson, 2011), and animals show stereotyped fear responses such as freezing and backing up (E. J. Gibson & Walk, 1960). However, being placed on the glass is more like being thrown off a cliff than exploring affordances from the edge. When infants are cajoled by their caregivers to cross, they do not show outward signs of fear (e.g., crying, backing away from the brink). Rather, they happily explore at the edge, but do not cross (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Tamis-LeMonda et al., 2008).

Moreover, when deciding whether to cross bridges varying in width, experienced crawlers and walkers scale attempts to bridge width, meaning they attend to affordances for crossing, but they treat large and small drop-offs under the bridge as equivalent, which indicates they do not respond based on the severity of a potential fall (Kretch & Adolph, 2013b). Thus, the evidence does not support an explanation based on fear of heights (Adolph et al., 2014).

A second interpretation is that locomotor experience teaches infants facts about drop-offs. This is not the case. Although infants’ everyday experience does not include locomotion over cliffs, gaps, steep slopes, bridges, or ledges, experienced infants respond adaptively on their first encounter with these situations in the lab. Infants do not exhibit within-session learning either within or across tasks (Adolph, 2000). When tested weekly, infants

behave the same way as those tested only once (Adolph, 1997; Adolph, Tamis-LeMonda, et al., 2008). And infants instantly update their perception of affordances to take changes in their bodies and skills into account, whether those changes occur naturally or are induced experimentally (Adolph, 1997; Adolph & Avolio, 2000; Adolph, Karasik, et al., 2010a).

Moreover, if infants were learning general rules, such as “large drop-offs are dangerous” or “be afraid,” they should avoid large drop-offs regardless of the posture in which they are tested. But they do not. Despite achieving accurate perception of affordances after 10–20 weeks of experience, learning does not transfer from earlier- to later-developing action systems. In an experienced sitting posture, infants correctly gauge how far they can lean over the edge of a gap; but in a novice crawling posture, they fall into the gap repeatedly (Adolph, 2000). Experienced crawlers avoid crawling over impossibly high cliffs and steep slopes, but novice walkers walk over the brink (Adolph, 1997; Adolph, Tamis-LeMonda, et al., 2008; Kretch & Adolph, 2013a). Experienced cruisers perceive affordances for cruising over gaps in a handrail, but novice walkers do not; and both groups step into impossibly large gaps in the floor (Adolph et al., 2011).

Variations in Both Body and Environment

Changes in the body or environment alter affordance relations. It is typically not a matter of simple geometric scaling: leg length to drop-off height, shoulder width to aperture size. Rather, affordances typically involve dynamic aspects of body and skills such as balance, strength, coordination, stretch, and deformability (Franchak & Adolph, 2014a). Infants’ ability to walk over gaps, barriers, bridges, and drop-offs depends more on their locomotor experience than their leg length (Kingsnorth & Schmuckler, 2000; Kretch & Adolph, 2013a, 2013b; Zwart, Ledebt, Fong, de Vries, & Savelsbergh, 2005). For infants, the head is the widest dimension and does not compress, so passage depends on head size (Franchak & Adolph, 2012). But torsos are widest in adults, and squeezing through apertures also depends on deformability of the torso (Franchak & Adolph, 2014b). See Figure 4.7g.

Perceiving affordances under changing body conditions requires generating and detecting information about the dynamic status of the body. Four- to 10-year-olds lift their feet to clear an obstacle based on both leg length and the variability of their movements relative to obstacle height (Snapp-Childs & Bingham, 2009). Eight- to 10-year-olds rotate their shoulders to fit through apertures based on both

shoulder width and side-to-side sway relative to aperture width (Wilmot & Barnett, 2011). Infants and children rotate their hands to fit them through apertures based on both absolute and scrunched hand size relative to opening size (Ishak, Franchak, & Adolph, 2014). Infants attempt to walk along a narrow ledge based on both body size and balance control relative to ledge width (Franchak & Adolph, 2012).

Bodies can change from day to day or even faster, so perception of affordances must be continually updated. Pregnant women update their perception of affordances for squeezing through narrow doorways based on changes in the size and compressibility of their growing torsos (Franchak & Adolph, 2014b); see Figure 4.7h. Nonpregnant college students, female and male, update their perception of affordances for passage after a brief period of experience wearing a “pregnancy pack” (Figure 4.7i). Experienced walking infants update their perception of affordances from trial to trial, depending on whether they are wearing lead- or feather-weight shoulder packs, or rubber or Teflon-soled shoes. They treat the same degree of slope as safe while wearing the feather-weight or rubber shoes, and as risky while wearing the lead-weight or slippery-soled shoes (Adolph & Avolio, 2000; Adolph et al., 2010a).

Animal Life at the Edge

Whether young animals have rudimentary motor skills, like humans, or are more adult-like and walk soon after birth, perceiving affordances requires continual updating of body-environment relations. Tree snakes decide whether to crawl, lunge, or avoid crossing gaps between branches based on their body length relative to gap size and the width of the destination branch (Jayne, Lehmkuhl, & Riley, 2014). Smaller snakes attempt larger gaps relative to body length because they have relatively more muscle to support the part of their body suspended midair (Jayne & Riley, 2007). Tree snakes explore affordances by extending their heads, viewing the drop-off, and tentatively “feeling out” the space between branches.

Unlike most crabs, hermit crabs do not form a protective shell of their own, so they have to find housing in the shells of deceased snails. As a young crab grows over a series of molts, it outgrows its home and has to find a suitable replacement (too small or too large makes it vulnerable to predators). So hermit crabs are almost always on the market. When a crab comes across an empty shell, it has to assess whether it is a suitable step up in housing. It does this by a series of measuring operations (Scully, 1986). It faces the aperture, rotates the shell, runs its major claws over the

exterior, then inserts each claw into the aperture. Switching is risky business, so if the shell is found suitable, the crab quickly exits its old shell and backs into the new one. The intertidal housing market is always tight, so crabs often resort to trading or stealing shells. Trades occur after crabs measure each other's shell. If it is a better fit, one crab raps the other (by banging its shell down on the other one). If the exchange is a good fit for both, then rapper and rappee swap (Hazlett, 1996). If the rappee declines, a shell fight may ensue.

Does all the measuring and rapping imply that lowly hermit crabs perceive affordances? They do, not only for shell selection, but also for passing through cracks and crevices in rocky tide pools. In an experimental setting, large hermit crabs avoid an aperture that is too narrow for passage in favor of a wide aperture, but small crabs make no distinction (Sonoda, Minoura, Gunji, Asakura, & Elwood, 2012). However, after small shells are glued to the exterior of their homes, small crabs also avoid the narrow aperture, suggesting that they quickly adjust to the wider dimensions and altered dynamics of their shell. Moreover, crabs can perceive affordances for passage based on visual information alone, without touching the aperture.

Summary: Actions Are Embedded

The specifics of perceiving and acting necessarily differ among different types of animals. But for human infants, snakes, monkeys, crows, robots, or any creature that must act adaptively in a changeable world, motor behavior cannot be stereotyped or preprogrammed. Learning cannot entail general rules or fixed solutions. The process of learning to learn may differ between human infants with very immature abilities (and altricial animals, such as rats and cats) and animals that can perform seemingly adult-like behavior soon after birth (precocial, like snakes and goats). But in all cases, the outcome is the same: Animals learn to explore the environment, guide actions prospectively, and select actions based on body-environment relations.

ENCULTURATED INTERACTION

Infants' world is inherently social. It is a world populated by other people. Caregivers, siblings, and peers offer opportunities for social interaction and social information for guiding motor action. Research conducted from the embodied and embedded approaches routinely exploits the persuasive power of social information to convince infants to reach for objects, use tools, crawl and walk down straight

paths, and navigate obstacles. But social influences are treated as a constant, like temperature or ambient lighting. When social information is explicitly considered, it turns out to be an important factor—at least in some conditions (see Carpendale & Lewis, Chapter 10, this *Handbook*, this volume). In a classic study, 12-month-olds crawled over an apparent “ambiguous” drop-off on the visual cliff when mothers posed frozen facial expressions of joy or interest; infants avoided when mothers posed fear or anger (Sorce, Emde, Campos, & Klinnert, 1985). By 18 months of age, infants are sophisticated consumers of social information. They defer to unsolicited advice—with mothers using their natural repertoire of dynamic facial expressions, vocalizations, and gestures (see Goldin-Meadow, Chapter 9, this *Handbook*, this volume)—only at the point of true ambiguity (Adolph et al., 2010a; Tamis-LeMonda et al., 2008). Infants ignore encouragement to walk down steep slopes beyond their ability and ignore discouraging messages to avoid shallow slopes within their ability. But at borderline slopes just at the limit of their individual ability, infants walk if mothers say “go” and stay put if mothers say “no.”

The path between motor behavior and social interaction is bidirectional. Social information can guide and facilitate motor action, and infants' motor actions elicit social behaviors from others. Bidirectional influences operate at every time scale. A parent's open arms may be the impetus for an infant's first walking steps; the advent of walking changes the nature of infants' social interactions with parents (Clearfield, 2011; Karasik et al., 2011).

Infants' world is social in a broader sense as well. Motor development is not just embodied and embedded; it is enculturated. Infants' physical environment has been shaped, designed, and constructed by people, sometimes with infants specifically in mind. Caregivers play a central role in structuring the environment for action. Caregivers decide where infants are, what positions they are in, when they are held or carried, what features of the environment are accessible, what infants wear, and what they eat. Such basic, everyday, childrearing decisions are so culturally ingrained and pervasive that we ignore their potential influence on development—that is, until we learn about childrearing practices from a different culture.

This section on enculturated interaction calls attention to the uncomfortable fact that most of what we know about development derives from a very limited sample of Western, White, middle-class children. We show that cultural differences in everyday childrearing practices have profound effects on motor development (see also Gauvain & Perez, Chapter 20, this *Handbook*, this volume). And

within a culture, motor development can instigate a cascade of developmental events in domains far afield from motor behavior.

Other Cultures, Other Paths

Research on human motor development, like every other area of psychology, represents less than 5% of the world's population (Adolph, Karasik, & Tamis-LeMonda, 2010a; Arnett, 2008; Heinrich, Heine, & Norenzayan, 2010; Jensen, 2013). Most participants in psychological research are American or from English-speaking or Western European countries. Worse, the American participants do not even represent the diversity of America's population. Most adult participants are students in psychology courses, meaning they are of college age, educated, affluent, and white. Most child participants are drawn from an even smaller sliver of the population: families with the time, resources, and interest to bring children to participate in laboratory studies (Fernald, 2010). The typical participant is from a Western, Educated, Industrialized, Rich, Democratic society, or, as Heinrich et al. (2010) dubbed it, WEIRD.

The fact that developmental research is conducted nearly exclusively with hyper-WEIRD children has several troubling implications. First, because WEIRD children share a more homogeneous childrearing environment, researchers cannot fully assess social and cultural effects on development (Fernald, 2010). Second, conclusions about what children at various ages can and cannot do (or should and should not do) are at best unproven and at worst incorrect. Without considering the rest of the world, norms for motor development are not likely to reflect the true human distribution (Adolph et al., 2010; Heinrich et al., 2010). The statistics on screening tests and milestone charts (see Figure 4.1) reflect the populations from which the sampled data are drawn. Even the selection of test items (e.g., "grasps cube," "crawls on hands and knees") is biased by the cultural lens of the researchers who devised the screening tests.

Third, there is something intellectually perverse about cross-cultural comparisons showing that infants in some "far-away land" (Asia! Africa! Eastern Europe!) are accelerated or delayed relative to WEIRD norms since the norms are likely not "normal" at all. Minimally, the World Health Organization developmental standards recommend norms based on a geographically diverse sample (Martorell et al., 2006). Fourth, as Lancy (2010) points out, ethnocentrism in developmental research has caused some researchers

to confuse nurture with nature by attributing cultural differences to biological differences. Indeed, motor development boasts an ignominious tradition of interpreting group differences in terms of racial differences, without considering effects of childrearing practices (Geber, 1958; Stanitski, Nietert, Stanitski, Nadjarian, & Barfield, 2000). For example, in contrast to WEIRD norms, Chinese infants reared in Hong Kong roll supine-to-prone before prone-to-supine (E. A. S. Nelson, Yu, Wong, Wong, & Yim, 2004). This cultural difference disappears for Chinese infants growing up in Canada (Mayson, Backman, Harris, & Hayes, 2009).

Finally, assuming biologically based, culture-free universals in motor development—a domain of development where such universals are typically assumed—is currently unwarranted. The prime candidates for universal status are the postural, manual, and locomotor skills (sitting, standing, reaching, walking) that are most valued across cultures. Ironically, some scholars who have argued for a more culturally contextualized psychology also assume that motor control is somehow impervious to cultural influences (Rozin, 2010). It is not. Childrearing practices have a profound influence on which motor skills children acquire, the age and sequence in which children acquire them, and the subsequent developmental trajectory.

Sleeping, Swaddling, Cradling, and Toileting

As illustrated in Figure 4.8, caregivers around the world adopt very different solutions for managing infants' sleep, containment, transport, and toileting—including sleep sacks, swaddles, cradleboards, and cradles (Adolph, Karasik, et al., 2010). For example, mothers in rural areas of northeastern China use sandbags to toilet their infants and to keep them safely in one location. For most of the day until they are 12–24 months of age, infants lay on their backs inside a bag of fine sand, with only their arms free to move. Infants buried in sand stay clean and dry (like kitty litter) and safely contained while mothers work (like a horizontal, immobilizing play pen). But restricted movement (coupled with social deprivation) retards motor development: Sandbag-reared infants sit and walk at later ages compared to infants not reared in sandbags (Mei, 1994). In central Asia, mothers use a "gahvora" cradle for toileting, sleeping, and transporting infants. Infants are swaddled and bound into the cradle so that mothers can safely transport them around the house and keep them out of harm's way. Infants stay clean and dry via external catheters that carry waste through a hole in the bottom of the cradle. They eat, sleep, and rest in the gavorah for up

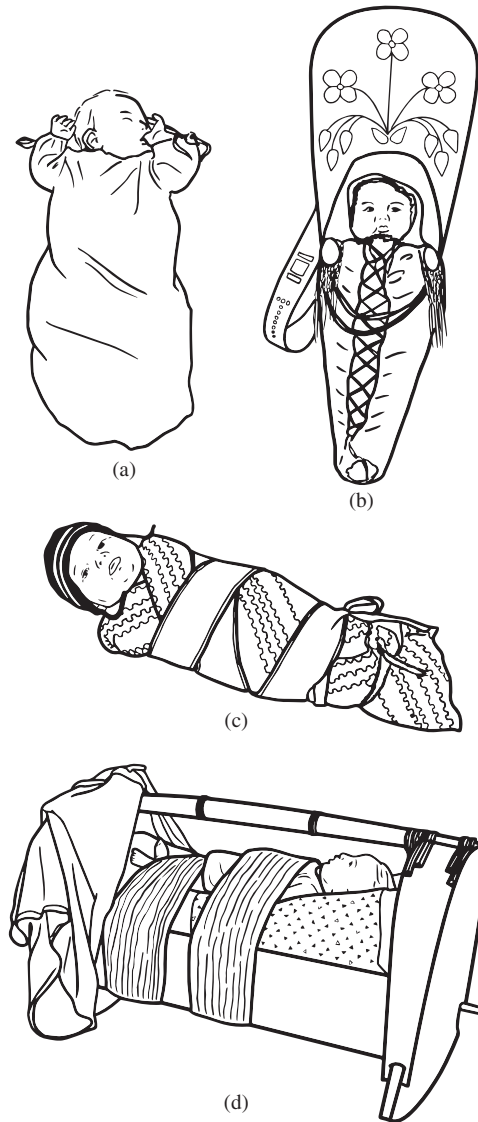


Figure 4.8 Examples of clothing and swaddling practices used for managing infants' sleep in various cultures. (a) Sleep sack or "nightie" currently in widespread use in the United States and Western Europe. (b) Infant strapped to traditional Nez Percé cradle board, once used by many Native American tribes throughout western North America. (c) Tightly swaddled Quechua infant from Peru. (d) Infant from Tajikistan in a gahvora cradle with binding straps, a common practice throughout much of central Asia.

to 20 hours a day, until they outgrow its confines at about 24 months of age (Save the Children, 2011).

Researchers need not travel to exotic locations to study effects of toileting and sleep position on infant motor development. In fact, the WEIRD research community is witness to a kind of grand "experiment" on the effects of sleep position. To reduce the incidence of sudden infant

death syndrome (SIDS), the American Academy of Pediatrics advised parents to place infants on their backs to sleep (Kattwinkel, Brooks, & Myerberg, 1992). The "Back to Sleep" campaign succeeded in reducing the incidence of SIDS, but resulted in unanticipated, less positive effects on infants' skulls and skills. Back-sleepers incur more plagiocephaly (skull flattening) than belly-sleepers (Joganic, Lynch, Littlefield, & Verrelli, 2009; Miller, Johnson, Duggan, & Behm, 2011), and they achieve skills such as head-lifting, rolling, belly crawling, hands-knees crawling, and tripod-sitting at later ages (Davis, Moon, Sachs, & Ottolini, 1998; Majnemer & Barr, 2005). In response, parents were advised to give infants "tummy time" when they are awake. More time in a prone position each day predicts earlier onset ages for prone skills (Dudek-Shriber & Zelazy, 2007; Kuo, Liao, Chen, Hsieh, & Hwang, 2008). Even something as seemingly mundane as a diaper exerts effects on motor development. Infants exhibit less mature walking patterns while wearing a cloth or disposable diaper compared with walking naked (Cole, Lingeman, & Adolph, 2012).

Infant Exercise

Caregivers in parts of Africa, the Caribbean, and India perform customary exercise, stretching, and massage as part of infants' daily routine (Adolph et al., 2010; Bril & Parrat-Dayana, 2008; Bril & Sabatier, 1986). As illustrated in Figure 4.9, infants' arms and legs are repeatedly extended and flexed, knees pulled to the chest and toes to the chin. The body is vigorously rubbed and anointed, suspended by the head or one limb, shaken, and tossed. Starting from the newborn period, infants are encouraged to hold their head up, support their body weight, sit, stand, and take steps (see also Figure 4.1c). To an observer from a WEIRD society, such practices seem rough and abusive. WEIRD people are taught that newborns must be handled like a fragile carton of eggs, with the head always carefully supported. Mothers from cultures that practice infant exercise and massage are just as appalled by WEIRD mothers' lack of vigorous motor handling and deliberate exercise (Keller, Yovsi, & Voelker, 2002); they are taught that infants must be trained to resist gravity, sit, and walk.

Rituals of infant exercise and stimulation affect motor development. Infants who receive deliberate training in sitting, standing, and stepping as part of daily childrearing routines sit and walk at earlier ages than infants who do not (Hopkins & Westra, 1988, 1989, 1990; Super, 1976). Such "natural experiments" point to cultural, not ethnic differences. Infants of the same ethnic origin do not show



Figure 4.9 Examples of formal massage and exercise practices used by caregivers in Africa, India, and the Caribbean to facilitate infants' motor development. Left to right: Passive stretching of infants' limbs; suspension and shaking by both arms, one arm, or ankles; encouragement to bear weight while standing upright and to take steps with support.

Source: "Maternal Handling and Motor Development: An Intracultural Study," by B. Hopkins and T. Westra, 1988, *Genetic, Social and General Psychology Monographs*, 114, pp. 379–408.

accelerated development if reared with traditional WEIRD practices. Moreover, WEIRD infants show the same facilitative effects of training in true experiments with random assignment to exercise and control groups. Infants given a few minutes of daily stepping practice for a few weeks retain upright stepping movements for longer durations and begin walking at earlier ages than infants who receive only passive exercise (Zelazo et al., 1972). A few minutes of gentle postural training from 2 to 3 months of age leads to accelerated postural, manual, and locomotor skills over the next 12 months (Lobo & Galloway, 2012).

To Infinity and Beyond

If humans have any species-typical behavior, it is surely bipedal walking. Although other species stand, hop, or bound on two legs, no other mammals habitually walk like humans. The anatomy of our hips and feet distinguish us from other primates. But after a century of research on walking, researchers still consider the endpoint of development in terms of the WEIRD students who populate our courses. We know relatively little about what people around the world can make their bodies do (Adolph, Karasik, et al., 2010; Adolph & Robinson, 2013).

Carrying loads is a necessary function in most of the world. In many places, children and adults carry water, firewood, and other burdens in buckets, parcels, or baskets balanced on the head—often more than their body weight (Bastien, Schepens, Willems, & Heglund, 2005). Remarkably, African women and Nepalese porters who routinely carry head loads can transport up to 30% of their body weight with no extra energy expenditure (Bastien et al., 2005; Heglund, Willems, Penta, & Cavagna, 1995). In contrast, obese Westerners maintain the same rate of energy use per kilogram as lean walkers, but still use twice as many calories to walk as someone half their size

(Browning & Kram, 2009). African load-carriers accomplish this extraordinary feat by altering the kinematics and kinetics of walking. The pendular motion so well described in WEIRD walkers is perfected in African load-carriers; they recover up to 80% of energy by transferring forward kinetic energy into vertical potential energy (Heglund et al., 1995).

Long-distance running is practiced around the world and celebrated in international competition. But the performance of Olympic marathoners is eclipsed by the customary practices of rank-and-file Tarahumaran Indians of north-central Mexico and !Kung bushmen in Botswana (Liebenberg, 2006; McDougall, 2009). Unarmed Tarahumaran hunters pursue deer through the harsh mountains of the Sierra Madre Occidentale for days until their prey drop from physical exhaustion. Bushmen do the same to hunt antelope in the Kalahari Desert until the animals succumb to fatigue or heat stress. Running for sport is even more remarkable. Tarahumarans' kickball races cover 150–300 km (Bennett & Zingg, 1935). Their extraordinary abilities are not due to unusual anatomy, but to intense cradle-to-grave physical conditioning that produces extremely lean bodies and highly efficient cardiovascular systems (Groom, 1971). In fact, the human foot may be engineered for long-distance running. Because Tarahumarans and Bushmen run barefoot or in light sandals instead of in sneakers, they land on the ball of their foot instead of the heel. As a consequence, they experience less force at foot contact and develop fewer running-related injuries (Lieberman et al., 2010).

Developmental Cascades

The developmental story does not end with motor skill acquisition. Rather, the story is just beginning. Motor development can instigate a cascade of events that leads

to learning and development in areas seemingly far afield from motor behavior and at time points far removed from the initiating event (Adolph & Robinson, 2013; Campos et al., 2000; Rakison & Woodward, 2008). For a long time, the idea of developmental cascades was largely unsubstantiated, but central nonetheless to prominent developmental theories (E. J. Gibson, 1988; Piaget, 1952; Thelen, 2005). Now researchers are inundated with evidence that motor experience can facilitate developmental change in perceptual, cognitive, and social domains. The evidence has awaited a change in zeitgeist from considering only single domains of development at a time to considering development of the whole baby in context (Oakes, 2009).

For example, postural skill and manual exploration at 5 months of age is a catalyst for academic achievement at 14 years of age (Bornstein, Hahn, & Suwalsky, 2013). How can this be? Developmental relations between such distant time points may seem like the spurious magic of statistics. But a tighter zoom reveals developmental and real-time relations between infants' posture, manual skills, object exploration, and perception, cognition, and social understanding. Specifically, the development of sitting facilitates improvements in reaching (Harbourne, Lobo, Karst, & Galloway, 2013; Rachwani et al., 2013) and visual-manual object exploration (Soska & Adolph, 2014). Improvements in manual skills, in turn, facilitate shifts in attention to object form (Soska, Adolph, & Johnson, 2010), changes in object appearance (Baumgartner & Oakes, 2013), object size (Libertus et al., 2013), and other people's intentions to grasp objects (Daum, Prinz, & Aschersleben, 2011; Loucks & Sommerville, 2012; Sommerville & Woodward, 2005).

Several lines of evidence support a causal developmental cascade rather than general maturation. Artificial motor experience instigates the same stream of developmental events. Prereaching infants who get a few weeks of self-generated experience retrieving objects with the help of "sticky mittens," Velcro-covered mittens that attach to objects without grasping, show short and long-term advances in reaching, grasping, and visual exploration of objects and people (Libertus & Needham, 2010, 2011; Needham, Barrett, & Peterman, 2002). A few weeks of training with posture and object interaction improves reaching, object exploration, and means-ends problem solving (Lobo & Galloway, 2008, 2012).

Simply performing a manual action (whether natural or with sticky mittens) for a few minutes prior to viewing a display leads to increased mental rotation abilities (Frick

& Wang, 2014; Mohring & Frick, 2013), visual anticipation of the outcomes of other people's actions (Cannon, Woodward, Gradeback, von Hofsten, & Turek, 2012) and enhanced attention to other people's intentions during goal-directed manual actions (Gerson & Woodward, 2013; Sommerville, Hildebrand, & Crane, 2008; Sommerville, Woodward, & Needham, 2005), other people's actions on the same objects (Hauf, Aschersleben, & Prinz, 2007), features that distinguish one object from another (Wilcox, Woods, Chapa, & McCurry, 2007; Woods & Wilcox, 2012), and causal relations between objects (Rakison & Krogh, 2012). Finally, motor development can both impede and enhance perception and cognition. Presitters and experienced sitters process faces holistically, but the acquisition of sitting appears to interfere with face processing (Cashon, Ha, Allen, & Barna, 2013).

New locomotor skills similarly instigate a cascade of developmental changes. Crawling experience is related to increased anger when infants' goals are thwarted (Roben et al., 2012), sensitivity to optic flow information for balance (Campos et al., 2000), differentiation of self-propelled versus externally caused object motion (Cicchino & Rakison, 2008), mental rotation abilities (Schwarzer, Freitag, Buckel, & Lofruth, 2013), more flexible memory (Herbert, Gross, & Hayne, 2007), more efficient use of distal and proximal landmarks (Clearfield, 2004), preferential looking to point light displays of crawlers compared with walkers (Sanefuji, Ohgami, & Hashiya, 2008), and greater activation in motor cortex while watching displays of infants crawling compared to walking (van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008).

Walking experience leads to more contacts with distal objects, more object carrying (Karasik et al., 2012), more carrying objects to interact with mother (Karasik et al., 2011), and more action directives from mother in response to moving bids (Karasik, Tamis-LeMonda, & Adolph, 2014). Walking experience also promotes more frequent and sophisticated social interactions with mother and more social looking (Clearfield, 2011; Clearfield, Osborne, & Mullen, 2008). And walking is associated with a significant increase in both receptive and productive language (Walle & Campos, 2014).

Artificially enhanced locomotor experience provides corroboration of a causal developmental cascade. Pre-crawling infants who get a few weeks of experience moving themselves around in a powered mobility cart (sitting up and operating a joy stick) show more postural compensation when exposed to peripheral optic flow

and earlier avoidance of a visual cliff than precrawlers who received no practice (Dahl et al., 2013; Uchiyama et al., 2008).

How should we interpret these cascades of development? Causal developmental links do not imply a linear causal chain: “For want of a nail, the kingdom was lost” or for want of self-generated object exploration, object cognition is lost. The developmental pathways are more reticulate, more redundant, more context specific, and more plastic than that. Developmental researchers must gather all of the usual suspects together and then figure out who done it, case by case. But we are still several chapters away from the end of that story.

Summary: Interaction Is Enculturated

In 1927, anthropologist Ales Hrdlicka proclaimed his “discovery” that infants from exotic cultures “run on all fours” like monkeys (p. 347). He considered crawling on hands and feet to be “anomalous,” “animal-like,” and “atavistic” (Hrdlicka, 1928), although a torrent of letters from WEIRD parents and contemporary descriptions of “bear crawling” by Gesell and McGraw argued otherwise. Hrdlicka’s comments were strangely prophetic of the recent discovery of 5 adult siblings in a remote area of Turkey who crawl on hands and feet (Humphrey, Skoyles, & Keynes, 2005). Early reports suggested that the Turkish crawlers were “atavistic throwbacks” to a more “ape-like” stage in human evolution (Tan, 2006), the cause of this “reverse evolution” being a genetic defect that resulted in incomplete development of the cerebellum (Turkmen et al., 2006). Such rash conclusions ignored the details of the case. The siblings crawl on their palms, as do typical human infants, not on their knuckles as do great apes, and they display a lateral sequence gait, typical of most mammals, not a diagonal sequence gait unique to nonhuman primates (Shapiro et al., 2014). Many (perhaps most) WEIRD infants exhibit bear crawling prior to walking (Adolph et al., 1998). People with cerebellar agenesis can walk on two legs and lead relatively normal lives (Boyd, 2010; Gardner et al., 2001). The other 14 siblings in the family crawled on hands and feet, providing models for their younger siblings. The parents accepted crawling in their adult children as a “gift sent by God.” And the Turkish crawlers began walking upright after their isolation was broken by researchers and physical therapists (Humphrey et al., 2005).

The case of the Turkish crawlers is clearly a missed opportunity to examine developmental relations between

brain, body, environment, childrearing, and behavior. It is also a missed opportunity to investigate how this unusual way of navigating and viewing the world might cascade into other areas of development. Rather than considering this case as a weird, isolated phenomenon, we should consider it as a natural experiment that could shed light on relations among developmental domains. More generally, research on motor development in non-WEIRD societies can challenge our assumptions about the plasticity of development by illustrating possibilities not previously imagined.

CONCLUSIONS: MOVING FORWARD

As Rosenbaum (2005) puts it, “motor control is the Cinderella of psychology” (p. 311), neglected in journals, textbooks, and psychology courses. This situation is peculiar, given that motor behavior is the only way to translate mental activity into actual activity. Developmental scientists bear reminding that motor actions are inherently psychological. Motor behavior entails more than producing muscle activity, joint angles, and forces. Adapting motor behavior to the constraints of body and environment requires perception, planning, decision-making, learning, and discovery of new strategies.

In the real world, motor behavior must be adaptive and the hallmark of adaptive behavior is flexibility. Motor behavior is constrained by body, brain, and environment, but anatomy is not destiny, the environment does not dictate behavior, and rearing does not preordain the future. Consider for example the aye-aye, a strange little lemur from Madagascar. Unlike other lemurs and monkeys, aye-ayes’ hands are highly specialized for extracting grubs from tree crevices. All of the digits are enormously elongated and extended further with pointed claws; the middle grub-picking fingers are fantastically long. One might expect, given their hand anatomy, that aye-ayes are like Edward Scissorhands, unable to grasp or manipulate objects. Indeed, close examination of food handling reveals difficulty producing thumb-fingertip precision grips. But aye-ayes’ unusual hand anatomy does not preclude dexterous object manipulation. Aye-ayes compensate with novel uses of the thumb compared to other lemurs. They wrap their long thumbs around small food items and grip larger items between the heels of their hands (S. M. Pellis & Pellis, 2012). Their manual behavior is exquisitely flexible.

As the most prevalent icon for motor development, and perhaps for all of child development, milestone charts such

as the one pictured in Figure 4.1 sport the imagery of progression from less to more sophisticated forms and spawn the sound bite of linking ages with stages. Perhaps due to the prominence of pioneers in developmental science such as Gesell, this iconography may have contributed to the widespread practice in developmental research of putting age on the x -axis and improvements on the y -axis and considering the job to be done.

Research on motor development has much more useful things to offer. Throughout its history, research on motor development has offered state-of-the-art recording technologies and analytic tools for studying the development of behavior. The accessibility of motor behavior to direct observation provides a unique window into developmental process. A burgeoning literature considers motor skill acquisition as both foundation and catalyst for development, cascading into perception, cognition, affect, social interaction, and social cognition. A full understanding of developmental process in these domains entails a complete picture of infancy—including, most notably, what infants *do* and how their activity affects what they experience.

Research in motor development has both inspired and been inspired by work in theoretical biology (e.g., dynamic systems, computational neuroscience), clinical science (using motor performance and plasticity as diagnostic tool and therapy), and computer science (robotics and artificial intelligence). Developmental robotics has embraced the challenge of understanding the development of adaptive, flexible behavior. Rigidly programmed simulations are being replaced by robot designs with changing bodies that act within changing environments and interact within larger robotic groups. In psychology, we should see these trends as a call to arms: Research on motor development has the potential to inspire a truly embodied, embedded, and enculturated developmental science.

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