CHAPTER 4

Motor Development

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Sure, every introductory textbook contains a chapter called “Motor Development,” usually paired with physical growth. But, the textbook inventories of infantile reflexes, motor milestones, and growth charts do not reflect the kind of work that currently characterizes the field. Most of us do, in fact, study perception-action coupling with the aim of understanding developmental changes in the perceptual, cognitive, social, and emotional processes that contribute to the adaptive control of motor actions. However, many developmental psychologists also study the formal structure of movements with the aim of using motor development as a model system for understanding more general developmental processes and principles. In recognition that motor development involves two kinds of research—using the formal structure of infants’ movements to elucidate general principles of development as well as a focus on developmental changes in the perceptual control of motor actions—we have, without apology, entitled this chapter, “Motor Development.”

The Formal Structure of Movements

A remarkable thing about motor skills is that movements are directly observable. Most domains of psychological
development are the hidden denizens of mental activity. The content of children’s thoughts, percepts, emotions, intentions, concepts, memories, and linguistic representations must be inferred from overt motor behaviors such as speech, gestures, facial expressions, and eye movements, or in more technically sophisticated labs, from images of brain activity. Likewise, the moment-to-moment time course of mental activities must be inferred from children’s vocalizations, patterns of looking behavior, manual and facial expressions, or from the traces of brain activity on an electroencephalogram. Descriptions of developmental changes in mental activity can be even more removed from direct observation because researchers frequently must rely on different tasks and procedures to study children at different ages, typically looking behaviors at younger ages and manual or vocal behaviors at older ages (Hofstadter & Reznick, 1996; Keen, 2003).

In contrast to the covert nature of mental events, motor behaviors are out in the open. As Gesell (1946) wrote in an earlier chapter in this Handbook, motor behaviors “have shape” (p. 297). Every wiggle and step occurs over measurable time and space. The traces of motor activity on a video monitor or three-dimensional motion-recording device are a direct readout of the movement itself. No inferential leap separates a motor skill from a description of its form. What you see is what you get.

Moreover, researchers can observe the changing form of children’s movements over multiple, nested time scales. The time-space trajectory of infants’ first awkward arm extensions can be compared with changes in the speed and straightness of the reaching trajectory over the trials in a single session, and across multiple sessions conducted over days, weeks, and months of practice. Milliseconds and millimeters are nested within larger time-space units. Changes in real time can be tracked directly over learning and development.

A benefit of being so conspicuously available to observation is that motor development makes a unique model system for studying general developmental processes—the origins of new behavioral forms; the extent to which development is patterned, orderly, and directional; the role of variability in facilitating or impeding development; whether developmental trajectories are continuous or stagelike; whether changes are universal across individuals and cultures; and so on. Such general issues of form and timing can be fruitfully addressed with a model system in which form and timing are transparent.

Inspired by Coghill’s (1929) example of linking developmental changes in the swimming patterns of salamander embryos with general principles of embryological development, the great pioneers in motor development—McGraw, Gesell, and Shirley—used changes in the form and temporal structure of infants’ movements as illustrations and existence proofs of general developmental processes. The focus on formal structure is beautifully exemplified in the line drawings that figured prominently in the work of the early pioneers (see Figure 4.1). Infants (like salamanders) are drawn abstracted from the surrounding context to highlight the changing morphology of the movements. Gesell (1946) described changes in the temporal structure and spatial configuration of infants’ crawling movements to demonstrate the existence of qualitative changes in human development. Likewise, contemporary researchers, led by Thelen and her colleagues (e.g., Thelen & Ulrich, 1991), have used the changing shape of infants’ reaching, grasping, kicking, stepping, crawling, walking, and jumping movements to illustrate developmental trajectories, propose general principles of developmental change, and speculate about biologically plausible developmental mechanisms.

Whereas most model systems are scaled-down versions of the target phenomenon, the beauty of using the changing shape of infants’ movements to understand development stems solely from the fact that we can see infants’ movements, not from their simplicity or
Perceptual Control of Motor Actions

Being out in the open has implications beyond visibility: The functional outcome of motor actions is inextricably bound to the biomechanical facts of children’s bodies and the physical properties of their environments. In A. Clark’s (1997) words, motor actions are always “embodied” and “embedded,” always performed by a creature with certain bodily capabilities and deficiencies and always performed in an environment with certain supports and hindrances. James and Eleanor Gibson’s concept of “affordances” captures the functional significance of embodiment and embeddedness: Possibilities for action depend on the fit between actors’ bodies and the surrounding environmental properties (E. J. Gibson, 1982; E. J. Gibson & Pick, 2000; J. J. Gibson, 1979). Whereas mental activity can be modeled profitably with a mathematical equation or a computer program at some remove from the limits and propensities of a physical body in a real world, a formal model of motor action is probably best simulated in a physically instantiated, free-wheeling robot (Brooks, 1991; Kuniyoshi et al., 2005). Like us, but unlike equations or computer software, robots are subject to physical forces.

Possibilities for action depend on all the myriad facts of embodiment. The size, shape, mass, compliance, strength, flexibility, and coordination of the various body parts can all affect the biomechanical constraints on action. The same functional outcome can require very different motor actions depending on the body’s status. For example, to bring their hands to their mouths at 7 weeks after conception, fetuses must raise their arms at the shoulder because their arm buds are so short (Moore & Persaud, 1993). To produce the same hand-to-mouth action several weeks later, fetuses must deeply bend their arms at the shoulder and elbow because their arms are much longer (Robinson & Kleven, in press).

Reciprocally, affordances for action depend on the mundane constraints of the environment in which infants’ bodies are embedded—the surfaces and media that support the body, the objects toward which movements are directed, and the effects of gravity acting on the various body parts. Again, fetal development provides a simple but compelling example. At 7 weeks post-conception, vigorous leg kicks can somersault the fetus through the amniotic fluid (deVries, Visser, & Prechtl, 1982). At 38 weeks, when the growing fetus is pressed against the walls of the uterus, the same muscle actions will fail even to extend the legs. After birth, when infants have ample room to move freely but have lost the buoyancy of a watery environment, the same muscle actions are subject to the pull of gravity. Now a vigorous kick merely flexes and extends the leg.

Our examples from fetal development illustrate a central and inescapable feature of motor action: The constraints of the body and the environment are continually changing. The facts of embodiment vary due to
developmental changes in the body (such as the lengthening and differentiation of the fetal arm) and the flux of everyday activities (Adolph, 2002; Reed, 1989). Carrying a toy under one arm, lifting a leg, or even drawing a deep breath create moment-to-moment changes in functional body dimensions and in the location of the body’s center of mass. Similarly, the environmental context is a shifting landscape, not a still life. Developmental changes in infants’ bodies and skills continually introduce them to new objects and surfaces and invite new possibilities for interaction. Observing children at a playground, for example, is a revelation in attention to new affordances (E. J. Gibson, 1992). The slide might serve as tent, downhill track, or uphill path; the monkey bars as canopy or ground surface; the swing set leg as barrier, maypole, or fire pole, depending on children’s changing propensities. The perfect robot simulation of infant motor development would require a machine whose body and environment develop.

Novelty in local conditions is the rule, not the exception. Behavioral flexibility is imperative, not optional. Contemporary researchers in motor development have focused so much of their attention on perception-action coupling because it is only through perceptual information that infants can guide their movements prospectively and adaptively (e.g., von Hofsten, 2003, 2004). Changes in the biomechanical constraints on action alter the forces required to produce the desired functional outcome. Perception specifies the current status of the body and the environment in which it is embedded, thereby giving infants access to the current constraints on action (J. J. Gibson, 1979). Perception allows actions to be planned prospectively and gears action to the environment. Motor actions complete the perception-action loop by generating information for perceptual systems and bringing the appropriate sensory apparatus to the available information. In Gibson’s (1979) words, “We must perceive in order to move, but we must also move in order to perceive” (p. 223). The interrelance between perception and action is so important for the adaptive control of motor actions that the chapter on motor development in the fifth edition of this Handbook (Bertenthal & Clifton, 1998) was entitled “Perception and Action.”

Chapter Overview

In addition to the chapter in the previous edition of the Handbook (Bertenthal & Clifton, 1998), the literature has amassed several detailed and comprehensive reviews of research on motor development, including chronologies of normative changes in motor skill acquisition and in-depth treatments of particular action systems such as looking, reaching, object manipulation, posture, and locomotion (e.g., Adolph, 1997; Adolph & Berger, 2005; Bushnell & Boudreau, 1993; Campos et al., 2000; E. J. Gibson & Schmuckler, 1989; Vereijken, 2005; von Hofsten, 1989; Woollacott & Jensen, 1996). Moreover, numerous articles and books present the two dominant theoretical perspectives in research on motor development, the dynamic systems and ecological approaches (e.g., Adolph, Eppler, & Gibson, 1993b; E. J. Gibson, 1988; E. J. Gibson & Pick, 2000; Goldfield, 1995; Smith & Thelen, 1993; Spencer & Schön, 2003; Thelen, 1995; Thelen, Schön, Scheier, & Smith, 2001; Thelen & Smith, 1994, 1998; von Hofsten, 2003, 2004; Zanone, Kelso, & Jeka, 1993). Proponents of dynamic systems views tend to stress the formal structure of movements with the aim of building a unified theory of development. Proponents of the ecological approach emphasize the functional links between perception and motor actions in an effort to understand the psychological underpinnings of motor development. However, most researchers agree that the ideas and methods of each approach are highly compatible and complementary (e.g., Bertenthal & Clifton, 1998).

Our aims are somewhat different from the previous efforts. Instead of presenting a comprehensive chronology of motor behaviors, updating earlier reviews of the various body parts and action systems, or evaluating the relative merits of the dynamic systems and ecological approaches, we focus on the concepts, questions, issues, and principles that excite researchers in motor development and that are likely to be of interest to readers in other areas of developmental psychology. Thus, our review is organized around ideas.

The chapter is divided into two large sections representing the two kinds of research programs that characterize current work in motor development. The first section treats motor development as a model system. We focus on the formal structure of movements and describe how researchers have used the changing shape of infants’ movements as a model system to address general issues of developmental processes and to propose general principles of change. The second section treats motor development as a perception-action system. We focus on the functional links between perceptual information and motor actions and describe how developmental changes in the interplay between perception and
action make infants’ motor actions increasingly flexible and adapted to features of the environment. In principle, findings generated by the perception-action approach could be used to draw general lessons about development. In practice, however, researchers have focused on the particular perception-action system that they are studying. In both sections, we present case studies that are especially useful illustrations of conceptual insights, fruitful arguments, and new ways of thinking about motor development. The case studies highlight motor development during the first 2 years of life to reflect the period where most research has focused.

**MOTOR DEVELOPMENT AS A MODEL SYSTEM**

Motor development in infancy is truly remarkable. Developmental changes in the form and structure of infants’ movements are tremendous in scope. At birth, babies can barely lift their heads. Eighteen months later, infants run across the room and navigate a tiny bit of food from plate to mouth with a pincer grip. Even to an untrained eye, many of infants’ dramatic accomplishments involve a clear mapping of babies’ clumsy head/eye, arm/hand, torso/leg movements onto adult-like looking, reaching, sitting, and walking movements. Conversely, some of the most dramatic developmental changes involve apparent disjunctions between behavioral forms—the disappearance, for example, of “newborn reflexes” and infants’ abandonment of transient forms such as “tripod sitting” (propped on the arms between the outstretched legs), crawling on belly and hands and knees, and sideways “cruising” while hanging onto furniture for support.

The case studies in this section highlight many of the dramatic accomplishments and disjunctions in motor development to illustrate general issues of developmental process. In addition, we focus on an equally remarkable aspect of infants’ movements: the ubiquity of movement across real time and development. Mundane eye scans, startles, wiggles, and flails of every body part from toes to tongue constitute a pervasive background of movement against which the more dramatic motor milestones appear in spotlight. Normally, background movements are so ubiquitous and seamless that they go unnoticed. However, when infants’ development goes awry due to prematurity or impairment, abnormalities in muscle tone, coordination, and motor control bring background movements to the fore. Simply breathing can become a struggle. Thus, we conclude this section by describing the background chorus of movements that are so typically overlooked by researchers and parents.

**Qualitative Changes**

Motor development has always been a testing ground for addressing the nature of developmental change. Is development continuous, marked solely by changes in the relative quantities of behaviors? Or, are changes discontinuous, such that development also entails qualitative, stagelike transformations?

**Developmental Stages**

The most widely recognized legacy of the early pioneers in motor development is their normative descriptions of stagelike changes in reaching, grasping, crawling, and walking and their focus on maturation as the driving force of development (Ames, 1937; Burnside, 1927; Gesell & Ames, 1940; Gesell & Thompson, 1934; Halverson, 1931; McGraw, 1945; Shirley, 1931). McGraw (1945) described visually guided reaching as a six-stage progression beginning with neonates who cannot unequivocally fixate a target object and ending with children in Stage 6 who retrieve objects casually and successfully, taking the target’s location and size into account without outward signs of “undue attention” (p. 99). Halverson (1931) described 10 milestones in the development of grasping, beginning with the “primitive squeeze” and culminating in the “superior-forefinger grasp.” Shirley (1931) described four stages in the development of walking: newborn stepping movements, standing with support, walking when led, and finally walking alone toward the end of the 1st year. Gesell, the consummate list-maker, described detailed series of stages for 40 different motor behaviors—58 stages of grasping a pellet, from newborns’ visual regard to toddlers’ “plucks pellet with precise pincer prehension” at the finale; 23 stages of crawling, from “passive kneeling” in Stage 1 to crawling on hands and knees in Stage 19; and so on (Ames, 1937; Gesell, 1933, 1946; Gesell & Thompson, 1938).

To modern researchers in motor development, the reifying of behaviors into stagelike lists seems old-fashioned, and attributing maturation as the driving force for infants’ progress through the various stages seems simplistic (Bertenthal & Clifton, 1998; Thelen & Adolph, 1992). Ironically, Gesell (1946), McGraw
(1935), and Shirley (1931) explicitly noted that most children straddled adjacent stages, skipped stages, reverted to earlier stages, exhibited behaviors that did not fit the structural descriptions of stages, and displayed vast individual differences. The enterprise of distilling real-time structure from variable motions and essentializing invariant sequences from developmental variability was instigated by a direct and conscious opposition to prevailing theories of conditioning and habit formation (Adolph & Berger, 2005; Thelen & Adolph, 1992). Likewise, the intense focus on maturation as the causal agent for development was a response to the extreme versions of behaviorism that were so popular at the time (Senn, 1975).

What’s New?

What then, might we take from the early pioneers? The so-called stages of infants’ motor skills highlight a central question in developmental psychology: Is there ever anything truly new? On the one hand, the qualitative changes in formal structure between earlier and later appearing stages of motor skills provide prima facie evidence that new behavioral forms can appear in development. Visual prehension, crude raking motions, and precise pincer prehension do not merely reflect changes in the speed, accuracy, and variability of a grasp. These behaviors are qualitatively different forms. Passive kneeling, belly crawling, hands-knees crawling, and Gesell’s 20 other stages of crawling share the common feature of prone body position, but these behaviors are qualitatively different in terms of the relevant body parts used for balance and propulsion and the temporal-spatial coordination of the various limbs. Such qualitative changes in the directly observable domain of motor skills provide a model system for evaluating arguments that development can entail qualitative change. One of the most influential ideas in research on cognitive development is that children’s mental structures can reorganize into qualitatively different, incommensurable ways of thinking (Carey, 1985; Piaget, 1954).

On the other hand, the reasonableness of each behavioral series points to core commonalities between stages in motor skill acquisition. Armed with modern, high resolution recording technologies that allow exquisitely detailed descriptions of infants’ movements, muscle actions, and force profiles, current research findings have tended to blur the distinction between stages by highlighting more continuous changes in the subtle elaboration and increasing precision of reaching and walking movements (Berthier, Rosenstein, & Barto, 2005; Bril & Breniere, 1992). Moreover, the notion that earlier appearing behaviors may be preformations of later appearing behaviors is a well-accepted concept in developmental psychology (Thelen & Adolph, 1992), as witnessed in von Hofsten’s (1984) prereaching, Meltzoff and Moore’s (1983) neonatal imitation, and Trevathan’s (1993) proto-communication. In cognitive development, Spelke and others (Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke & Newport, 1998) argue that core concepts presage mature thinking in domains of physical, biological, and psychological reasoning. On these views, the adultlike endpoint is an elaboration of the initial concept, rather than a metamorphosis or true transformation.

Emergent Developments

The most prevalent view of development among both academics and laypersons is that developmental changes are driven by some factor or set of factors, located in the environment, the brain, or the genes. These factors, either acting alone or in combination, are the drivers—the causal agents—of developmental change. An alternative systems view of development was spearheaded largely by Thelen and colleagues’ work on infants’ leg and arm movements (e.g., Thelen & Smith, 1994). On this account, motor development, like developmental changes in any domain, may result from the spontaneous self-organization of the various components in the system. The emergent product of the mix is different from and greater than the sum of its component parts.

Brain-Based Explanations

Although most modern researchers scoff at Gesell’s idea that neural maturation drives motor skill acquisition lockstep through a series of stages, many modern researchers assume that neural maturation plays a pivotal role in motor development. Researchers presume that differences in pre- and postnatal neural maturation contribute to differences in locomotor abilities between precocial animals such as chicks and altricial animals such as rats (Muir, 2000). Maturation of postural mechanisms in the central nervous system (CNS) underlie age-related changes in children’s response to balance disruptions (Forssberg & Nashner, 1982; Riach & Hayes, 1987; Shumway-Cooke & Woollacott, 1985).
Maturational changes in the speed of information processing facilitate walking onset toward the end of infants’ 1st year (P. R. Zelazo, 1998; P. R. Zelazo, Weiss, & Leonard, 1989). Alternatives to maturation tend to emphasize experience-driven changes in the CNS. For example, some of the differences in motor precocity between chicks and rats may result from the longer period of time that chick embryos spend moving their legs compared with rat fetuses prior to hatching or birth (Muir & Chu, 2002). Experience maintaining balance in a variety of upright postures and tasks may reorganize how the CNS controls the various body parts when balance is disrupted (Ledebt & Bril, 1999; Roncesvalles, Woolacott, & Jensen, 2001).

Modern brain-based explanations for motor development are in good company. Theoretical debates about the sources of cognitive and perceptual development also center around maturation versus experience-driven changes in the CNS (e.g., M. H. Johnson, Munakata, & Gilmore, 2002; Spelke & Newport, 1998). Researchers’ shared partiality for the brain over other body parts makes sense: The brain is of psychological interest, whereas the elbow and the knee are not. Using the developmental trajectory of infants’ leg movements as an extended case study, we describe the alternative possibility that no factor, including the brain, is logically responsible for development. In this alternative account, changes in more homely factors normally outside the purview of psychologists’ interest, may be the critical facilitators of development. Undoubtedly, important changes in the brain and nervous system occur throughout development. At issue is whether these changes must enjoy a privileged status in explaining developmental progress.

**Alternating Leg Movements**

We begin with the observations and puzzles that originally fascinated researchers. The observations are these: Newborn infants perform alternating leg movements if an experimenter holds them upright with their feet against a solid surface (see Figure 4.2a). The “steps” are painfully slow and exaggerated (Forssberg & Wallberg, 1980; Shirley, 1931), but, like mature walking, first one leg moves and then the other. At approximately 8 weeks of age, upright stepping movements disappear. Infants either stand rooted to the ground (McGraw, 1935) or perform bouncing movements by simultaneously flexing both legs and then extending them (J. E. Clark, Whitall, & Phillips, 1988; McGraw, 1932). Upright stepping returns toward the end of the 1st year when infants begin to walk with support and eventually to take independent walking steps. This U-shaped developmental progression raises three intriguing puzzles:

1. What makes newborns step?
2. Why do infants exhibit the alternating pattern rather than some other pattern of leg movements?
3. What makes upright stepping disappear and then reappear months later to cause the U-shaped trajectory?

**Reflexes**

Puzzle 1—why newborns step—is a question about proximal cause. The most commonly held answer is that the movements are a spinal reflex elicited by the upright position and the feeling of the floor beneath infants’ feet (McGraw, 1945; P. R. Zelazo, 1976, 1983). In fact, stepping is prominently featured in most developmental textbooks as an example of a newborn reflex (e.g., Berk,
newborn stepping does not fit well with a traditional notion of a reflex. In contrast to an eye blink response to a puff of air or a withdrawal response from a pinprick, stepping is inconsistent across infants and instances (Saint-Anne Dargassies, 1986) and particular eliciting stimuli are not necessary. Infants exhibit stepping movements on walls and ceilings in sideways and upside-down positions (Andre-Thomas & Autgaerden, 1966; Peiper, 1963). They step spontaneously without any stimulation to the bottoms of their feet while in the uterus (Prechtl, 1963) and while held with their legs dangling in the air (Thelen & Fisher, 1982; Touwen, 1976; B. D. Ulrich, 1989). Moreover, as illustrated in Figure 4.2b, infants frequently kick their legs in the same alternating pattern while lying on their backs (Thelen, 1979; Thelen, Bradshaw, & Ward, 1981; Thelen & Fisher, 1982, 1983b). Stepping and kicking appear so similar in that stick diagrams of stepping look like kicking if you turn the figure sideways (see Figure 4.2c).

Stepping and kicking movements are most frequent when infants are aroused and fussy but not crying and tonically rigid (e.g., Thelen, 1981a; Thelen, Fisher, Ridley-Johnson, & Griffin, 1982). Similarly, when late gestation rat fetuses and newborn rat pups are aroused by sensory stimulation or drug injections, they also increase the frequency of alternating stepping movements in their fore and hind limbs while held in various positions (Robinson & Smotherman, 1992). Thus, some researchers view newborns’ alternating leg movements as a spontaneous by-product of arousal, rather than a reflex (Thelen et al., 1982). The upright posture, pressure of the experimenter’s hands around the chest, feeling of the floor under the feet, and so on may increase infants’ arousal. As infants become aroused, energy flows through their muscles and powers up their legs (Thelen & Smith, 1994).

**Pattern Generators**

Puzzle 2—why the alternating pattern instead of some other pattern—concerns the real-time, moment-to-moment control of movements. In principle, newborns might move one leg at a time or both legs simultaneously (and they occasionally do), so why might the alternating pattern predominate? Neither a spinal reflex nor an arousal account specifically addresses the alternation between the legs. The similarity in form between newborn stepping and later walking has led many researchers to view newborn stepping as an example of a core competence that is later co-opted and adapted for functional purposes in mature walking (Spelke & Newport, 1998). The core propensity to move the legs in alternation might reside in animals’ neural anatomy in a so-called central pattern generator (e.g., Forssberg, 1985; Muir, 2000; Yang, Stephens, & Vishram, 1998)—a neuronal network in the spinal cord that produces locomotor movements of the legs through rhythmic alternations in flexor and extensor muscles (Grillner, 1975; Grillner & Wallen, 1985; Kiehn & Butt, 2003). Indeed, anencephalic infants step (Monnier, 1973), indicating that higher brain regions are not necessary for performing the movements. Similarly, insects and spinal preparations of rats, cats, lampreys, and chicks produce alternating bursts of neural activity in the flexor and extensor muscles responsible for locomotion (e.g., Orlovsky, Deliagina, & Grillner, 1999).

Intact animals, however, may display the alternating pattern without the benefit of (or despite the availability of) a neural pattern generator. Although researchers cannot study the neural activity in the isolated spinal cords of human infants, muscle activations revealed by electromyography are not strictly consistent with the notion of a central pattern generator. In some studies, infants’ alternating leg movements do not appear to result from rhythmic bursts of flexor and then extensor muscles. Instead, infants bend their legs to kick or to step by co-contracting flexor and extensor muscles in their hips and ankles simultaneously (Forssberg, 1985; Thelen & Cooke, 1987; Thelen & Fisher, 1982, 1983b). Because the flexor muscles are stronger, the leg bends. Infants straighten their legs without the need for muscle activation. Instead, the springiness of the leg reverses the direction of motion from flexion to extension and the force of gravity pulls the leg straight (Thelen, 1996).

In fact, co-contraction of the muscles that power up a movement and the muscles that oppose the movement may be the norm rather than the exception in infants’ movements (e.g., Forssberg, 1985; Forssberg & Wallberg, 1980). Co-contraction makes movements slower and stiffer and can even freeze a movement (as when crying infants become tonically rigid or when we “make a muscle” by co-contracting biceps and triceps). Although undifferentiated muscle actions are emblematic of early periods in skill acquisition and produce clumsy-looking, energetically costly movements (Damiano, 1993), co-contraction may serve a useful function by “chunking” individual muscles into larger groups and thereby simplifying the control prob-
Central pattern generators, like any other neural mechanism in the CNS, can only control muscle forces (Pearson, 1987; Winter & Eng, 1995). Movements, however, are composed of multiple forces (Bernstein, 1967; Woollacott & Jensen, 1996; Zernicke & Schneider, 1993). The net force responsible for a movement can be decomposed into the active forces produced by the muscles and the passive forces produced by the springiness and stickiness of the muscles and joints, gravity, inertia, and the motion-dependent torques created by moving other body parts (the hip bone is connected to the thigh bone, etc.). If you lift your arm from a stationary position at your side, muscle force contributes significantly to the total force required for the movement. However, if you drop your arm downward from overhead, the movement is nearly entirely controlled by gravity and inertia. If you wave your upper arm while allowing your wrist to go limp, the movement of your hand results from motion-dependent torques. Thus, movements with the same outward appearance can be caused by very different patterns of muscle activation (reciprocal enervation, co-contraction, etc.). The CNS acts more like a team player than a star soloist in determining real-time movement outcomes.

Behavioral Flexibility

A final piece to Puzzle 2 concerns the flexibility of the alternating pattern. A central pattern generator that can flexibly modulate, alter, and discard its pattern to suit the task is just a fancy name for the CNS (Thelen & Spencer, 1998). Although leg alternation normally predominates, it is not obligatory, and although leg alternation is displayed by anencephalic infants, the movement pattern is not impervious to perceptual feedback and supraspinal influences. One reason for alternation may be movement economics. Lifting both their legs off the floor simultaneously while an experimenter holds infants upright under their arms and bending and straightening both legs together while infants lie on their backs might require infants to exert more work in their abdominal and torso muscles than lifting their legs in alternation (Thelen & Smith, 1994). Under task constraints that alter the balance of effort, infants switch from alternating to simultaneous leg movements. An elastic yoke between the legs of 4-month-olds caused infants to switch from predominately alternating and single leg movements to simultaneous movements that did not require them to pull against the yoke (Thelen, 1994). Similarly, in several studies, a pliable yoke between the hind limbs of fetal rats and newborn rat pups elicited a switch from alternating and single leg kicks to simultaneous leg movements (Robinson & Kleven, in press). A yoke between the fore and hind limbs on one side elicited increased synchrony between that pair of limbs. In other words, human infants and baby rats might simply perform the easiest pattern of movements given the current circumstances.

Like simultaneous leg movements, single-leg movements can also predominate when researchers arrange the appropriate contingencies. With the new biomechanical constraints introduced by a weight around one ankle, 6-week-old infants maintained their overall kick rate relative to baseline, but they broke up the alternating pattern by kicking more frequently with their unweighted leg (Thelen, Skala, & Kelso, 1987). With a tiny weight attached to one leg, 1- and 2-day-old rat fetuses produced more kicks on their unweighted leg and they scaled their kick frequency to the size of the weights (Brumley & Robinson, 2002, in press).

With the introduction of motivational factors, infants kick a single leg quite purposefully. In the most popular paradigm, researchers link an infant’s leg movements with a desirable goal by attaching one end of a soft ribbon to the infant’s foot and the other end to an overhead mobile. Dozens of experiments by Rovee-Collier and her colleagues showed that infants increased the frequency and size of leg kicks when their movements caused the mobile elements to jiggle (e.g., Rovee & Rovee, 1969; Rovee-Collier & Gekoski, 1979; Rovee-Collier, Sullivan, Enright, Lucas, & Fagen, 1980). In terms of intralimb kinematics and electromyogram (EMG) patterns, the spontaneous baseline kicks were continuous with the exploratory kicks during acquisition and the intentional kicks during extinction, meaning that infants harnessed the available movements for functional action (Thelen & Fisher, 1983a). After learning the contingency with one leg, 3-month-olds quickly learned to kick the formerly noncontingent leg when the ribbon was switched (Rovee-Collier, Morrioniello, Aron, & Kupersmidt, 1978). Perhaps most impressive in terms of flexibility, 3-month-olds learned to flex and extend their contingent leg to particular criterion angles under a strict conditioning arrangement that required these specific joint angles to activate the mobile (Angulo-Kinzler, 2001;
Regressions

Puzzle 3—why upright stepping disappears and subsequently reappears—concerns regressions and continuity over development. A long-held explanation credits neural maturation as the primary factor in driving the U-shaped developmental trajectory (e.g., Forsberg, 1985, 1989; Forsberg & Wallberg, 1980; McGraw, 1940, 1945). On this account, cortical maturation suppresses newborns’ spinally generated stepping movements at 8 weeks. With increasing myelinization of the cortical-spinal tract, stepping movements reappear under volitional, cortical control at 8 months. Finally, maturation of neural structures and circuitry increases information-processing speed and efficiency so that infants walk independently at approximately 12 months (P. R. Zelazo, 1998; P. R. Zelazo et al., 1989).

Several lines of evidence indicate that continuity may underlie the apparent regression. That is, alternating leg movements are only masked in an upright position; they do not disappear. One line of evidence is that infants continue to display spontaneous kicking movements during the same 2- to 8-month time period when they do not display upright stepping (Thelen, 1979; Thelen & Fisher, 1982). Given the structural similarities between kicking and stepping in their real-time trajectories, the difference in developmental trajectories appears due to posture rather than propensity.

A second argument for continuity is that normally nonstepping 2- to 7-month-old infants exhibit alternating steps when they are supported over a motorized treadmill (Thelen & Ulrich, 1991). Like stepping in newborns, stepping in older treadmill walkers appears to be nonvolitional; infants rarely look down or show interest in the movement of their lower limbs (Thelen, 1986). However, as in kicking, the legs are responsive to the biomechanical context. In several studies, infants altered the speed of their steps in accordance with treadmill speed (Thelen, 1986; Vereijken & Thelen, 1997; Yang et al., 1998). With one leg on a faster moving treadmill belt and the other leg on a slower moving belt, infants maintained alternating movements. But, to do so, they relinquished the normal 50% phasing relationship between the legs and treadmill walking looked like limping (Thelen, Ulrich, & Niles, 1987). When the movements of one leg were disrupted by manually holding the leg in place or by pulling the leg back at a speed faster than the moving treadmill belt, infants typically adapted by keeping only one leg in the air at a time (Pang & Yang, 2001). In the event that infants momentarily lost the alternating pattern, they quickly regained it in the step immediately following the disturbance.

A third line of evidence concerns the effects of practice. When parents give their infants daily practice moving their legs in an upright position as part of an experimental training regimen or as part of a cultural belief in infant exercise, infants retain the alternating movements for longer periods (N. A. Zelazo, Zelazo, Cohen, & Zelazo, 1993; P. R. Zelazo, Zelazo, & Kolb, 1972) or display the movements continuously over the 1st year of life (Konner, 1973). Similarly, regular practice stepping on a motorized treadmill results in a higher frequency of alternating steps and more adult-like muscle actions (Vereijken & Thelen, 1997; Yang et al., 1998). A related argument for continuity is that typically developing infants who receive regular practice with stepping movements begin to walk at younger ages compared with infants in control groups who did not receive daily practice and infants in cultures that do not emphasize the exercise of upright postures (Hopkins & Westra, 1990; Keller, 2003; Super, 1976; P. R. Zelazo et al., 1972, 1989). Similarly, children with Down syndrome who receive daily practice walking on a treadmill begin walking independently at younger ages than matched controls (D. A. Ulrich, Ulrich, Angulo-Barroso, & Yun, 2001).

Contextual Factors

The remaining piece to Puzzle 3 concerns why upright steps might normally be masked. Just as nonneural, biomechanical factors may constrain and facilitate movements in real time, the culprit in the developmental course of infants’ leg movements may be the decidedly nonneural factor of leg fat. Over the first few months of life, normal gains in leg fat typically outstrip gains in muscle strength (Thelen, 1984b). On this leg-fat account, supine kicking may continue during the same period when upright stepping disappears because supine kicking requires less muscle strength than upright stepping (think of performing bicycling movements with your legs in a supine position compared with marching movements while standing upright). Gravity assists hip flexion while infants are lying down by pulling infants’ thighs toward their chests, but gravity works against lifting the legs while infants are standing up by pulling the leg downward (Thelen, Fisher, & Ridley-Johnson,
Accordingly, naturally slimmer infants produce more upright steps than chubbier ones (Thelen et al., 1982). When infants’ legs were loaded with small weights to simulate normal gains in leg fat, previously stepping infants stopped stepping (Thelen et al., 1984). Conversely, when infants’ legs were submerged in a tank of water to alleviate the effects of gravity, nonstepping infants stepped once again.

Consistent with the leg-fat explanation, nonstepping infants might exhibit steps on a motorized treadmill because the treadmill belt provides the necessary energy to lift the leg against gravity. The treadmill stretches the leg backward and allows it to pop forward like a spring (Thelen, 1986). Alternating steps may predominate over simultaneous leg movements because lifting both legs together requires more work in the abdominal muscles. Regular practice moving the legs in an upright posture may prolong stepping movements beyond the 8-week cutoff and accelerate walking onset before the end of the 1st year by building up the requisite strength for infants to lift one leg through the air and to support their body weight on the other leg. Specificity of training effects provides further evidence that practice builds strength. Training regimens for newborn stepping do not facilitate newborn sitting and vice versa (N. A. Zelazo et al., 1993).

**Facial Wiping**

Our choice of newborn stepping as an extended case study was not accidental. For nearly a century, infants’ alternating leg movements have served as a favored model system for illustrating general principles in maturationist (e.g., McGraw, 1940), learning (e.g., P. R. Zelazo, 1998), core competence (e.g., Forssberg, 1985; Spelke & Newport, 1998), and dynamic systems (e.g., Thelen & Smith, 1994) views of development. The favored status of infants’ leg movements stems both from the centrality of walking for human functioning and from the fascinating puzzle of developmental regressions. Our aim here is to illustrate the plausibility of the argument that, at least in principle, factors outside the province of the CNS may sometimes be the critical facilitators of development. Toward that end, we describe a lesser known, but equally fascinating example.

Just as alternating leg movements are a highly patterned response in the behavioral repertoire of human infants, facial wiping is a highly stereotyped response for rats. The animals bring one or both forepaws to their ears and stroke downward toward their nose in bouts of single or simultaneous limb movements (Berridge, 1990). Under normal circumstances, adult rats exhibit facial wiping during grooming. In an experimental arrangement, a noxious stimulus such as an infusion of quinine or lemon into the mouth elicits facial wiping (Grill & Norgren, 1978). Like the U-shaped trajectory of infants’ leg movements, facial wiping also exhibits a developmental regression. Facial wiping to a lemon infusion appears in completely exteriorized fetal rats at 20 to 21 days of gestation (rats have a 21-day gestation). After birth, facial wiping to lemon disappears. The classic limb movements to a noxious lemon infusion reappear 11 days later when rats stand up on their hind legs and wipe their face with their front legs (Smotherman & Robinson, 1989).

Like stepping in human infants, the propensity for facial wiping in rat pups is merely masked; the movements have not actually disappeared. At 19 days of gestation, the age when completely exteriorized fetuses fail to facial wipe to a lemon infusion, partially exteriorized fetuses exhibit wiping movements inside the amnion (Robinson & Smotherman, 1991). What factor might underlie the dramatic difference in behavior caused by the subtle difference in context? Between 19 and 20 days of gestation, fetuses acquire the ability to stabilize their head. For 19-day-olds, the amnion provides an important stabilizing function. The amniotic membranes hold the head steady and help the paws to contact the face.

Why, then, do the movements disappear after birth? In newborn pups, the facial wiping behavior competes for expression with a strong tendency to maintain contact against a surface with their belly and all four feet (Pellis, Pellis, & Teitelbaum, 1991). With forelimbs freed from contact with the ground by neck-deep immersion in water, 1- to 3-day-old rat pups exhibited facial wiping to lemon (Smotherman & Robinson, 1989). Although the urge to keep the body pressed against a contact surface dissipates after a few days, full-blown facial wiping awaits sufficient postural control for rats to stand up on their hind legs at 11 days postbirth. In the meantime, 7- to 9-day-old rat pups compensate for inadequate balance by improvising the necessary support (Robinson & Smotherman, 1992). For example, they support their bodies on their elbows and lower their head for simultaneous wiping between the two forepaws.

**Rate-Limiting Factors**

The factors involved in unmasking facial wiping in rat pups are reminiscent of the role played by the treadmill,
the tank of water, and the supine position in unmasking alternating leg movements in human infants. The amniotic, water tanks, and so on served as external scaffolds that temporarily replaced missing elements and thus promoted the expression of the target behaviors (Smotherman & Robinson, 1996). In a sense, the ability to lift the forelimbs to the face or to move the legs in an alternating pattern resides as much in the scaffolds as in the infants.

Both case studies—alternating leg movements and facial wiping—highlight the epigenetic nature of development (Oyama, 1985). That is, current behavior emerges from the changing interplay between the various components in the organism and the various components in the local environment (Smotherman & Robinson, 1996). New developments might be more than the sum of the component parts and new behavioral forms might arise as the product of spontaneous self-organization.

Given a particular environment, each organismic component must be above some threshold level of developmental readiness to produce the target behavior. Many writers refer to the set of component abilities, processes, propensities, and bodily features as a “confluence of factors” (Bertenthal & Clifton, 1998, p. 87; Freedland & Bertenthal, 1994, p. 26; Spencer & Schönér, 2003, p. 397; Thelen, 1995, p. 83) to emphasize the fluid and changeable nature of the entire behavioral system. Like a developmental chemistry experiment, over time, factors may enter and disappear from the mix and the various combinations and interactions of components may result in new behaviors. At any given point in development, the critical, rate-limiting factor that triggers the system to reorganize into a new configuration might be a psychological function governed by the CNS (e.g., motivation, balance control), or it might be a more peripheral factor such as gravity or leg fat.

Developmental Trajectories

Developmental regressions underscore the importance of describing developmental trajectories, especially in individuals. Motor development and physical development are uniquely suited for such a task because the dependent variables—movements and body growth—can be observed and mapped directly. Historically, research in motor development has always recognized the value of careful, detailed descriptions of individual developmental trajectories. McGraw’s (1935) daily observations of identical twins Jimmy and Johnny are the most famous example. However, other examples abound. Researchers have tracked the course of fetal motility (Devries et al., 1982; Robertson, 1990), infants’ eye movements (von Hofsten, 2004), rhythmic stereotypes (Thelen, 1979, 1981a), treadmill-elicited stepping (Thelen & Ulrich, 1991; Vereijken & Thelen, 1997), reaching (Clifton, Muir, Ashmead, & Clarkson, 1993; Corbetta & Bojczyk, 2002; Halverson, 1931; Spencer et al., 2000; Thelen et al., 1993; von Hofsten, 1991), crawling (Adolph, Vereijken, & Denny, 1998; Freedland & Bertenthal, 1994), walking (Bril & Breniere, 1989, 1992, 1993; Shirley, 1931), crawling and walking over slopes (Adolph, 1997), everyday crawling and walking experience (Adolph, 2002; Garciaguirre & Adolph, 2005b), and stair-climbing (Gesell & Thompson, 1929).

What can be gained from so much complex, individualized description? What new understandings might warrant the additional work and expense of microgenetic analyses? Although cross-sectional studies can identify interesting developmental milestones, microgenetic descriptions of individual children may yield a more accurate picture of developmental progress (see Siegler, Chapter 11, this Handbook, this volume). The rate and amplitude of change vary across children and sometimes critical features in the shape of the trajectory vary across children (Corbetta & Thelen, 1996). Thus, one argument for microgenetic analyses is that averaging across children and time-based observations can lead to erroneous assumptions about the underlying trajectory (Lampl, Johnson, & Frongillo, 2001). Such errors can, in turn, misinform theories about the mechanisms of developmental change and distort the design of subsequent studies to test the putative mechanisms.

A second argument for microgenetic analyses is that based on individual trajectories, researchers can identify possible causes of change (Ledebt, 2000; Thelen & Corbetta, 2002). For example, reaching for small objects shows a zigzag trajectory over the 1st year of life. First, infants reach with two hands for small objects, then one hand, then they revert to the less efficient bimanual reach, then back to one hand (Fagard, 2000). The timing of the zigzag, however, varies across infants. Microgenetic observations of individual children suggested that the reversion to bimanual reaching might stem from an increased coupling between the arms in walking. In the same few weeks when infants reverted to bimanual reaching, they began to walk using the typical “high-guard” position of the arms to help themselves keep balance (Corbetta & Bojczyk, 2002). In subsequent weeks, as the arms gradually lowered and differentiated into a
One Step Backward, Two Steps Forward

The path of development is often tortuous and uneven. Sometimes when skill performance reaches asymptote, the only route to forward progress involves a detour. Infants may need to relinquish the accuracy, efficiency, and stability that they have fought so hard to attain with an earlier developing skill in order to make progress with a later developing skill that will eventually enable a higher level of functioning. In terms of both form and function, development can be a process of moving one step backward for every two steps forward (P. H. Miller, 1990; P. H. Miller & Seier, 1994).

The transition from crawling to walking provides a wonderful illustration of uneven developmental progress. After weeks of steady improvement, infants achieve high levels of performance in crawling on hands and knees (Adolph et al., 1998; Freedland & Bertenthal, 1994). Their quadruped gait is fast, beautifully modulated, and highly functional. Ironically, the switch from the earlier developing skill of crawling to the more mature skill of walking requires expert crawlers to cope with an initial decrement in performance. At first, upright walking is slow, variable, and so teeming with errors that infants may fall after every few steps (Shirley, 1931). On some level, infants may be aware that their new upright skill comes with a cost. Newly walking infants sometimes revert from walking to crawling if they want to get somewhere quickly (McGraw, 1935; Zanone et al., 1993). Nonetheless, many researchers have noted that children appear pulled, perhaps by the sheer novelty of the new skill or the motivation for advancement, toward relinquishing the old in favor of the new (e.g., Rosander & von Hofsten, 2000; Shrager & Siegler, 1998; von Hofsten, 2004). New walkers prefer to face locomotor obstacles in their less efficient upright posture than in their more functional and familiar crawling posture (Adolph, 1997). When placed in their old familiar crawling posture at the top of an impossibly steep slope, new walkers sometimes stand themselves up, walk helplessly over the brink, and fall.

Like the developmental change from crawling to walking, the acquisition of locomotion involves an initial decrement in performance. Infants must relinquish the hard-won stability of a stationary posture for a new, more precarious dynamic posture in which they are likely to fall. After infants finally acquire sufficient arm strength to push up and keep balance on all fours, they may spend weeks practicing their new balancing act, sometimes rocking back and forth rhythmically (Adolph et al., 1998; Gesell & Ames, 1940; Goldfield, 1989; Thelen, 1979), as if aroused and eager to go, but stuck with both hands on the ground. The developmental transition from expert, controlled quadruped to novice, falling-down walker requires infants to give up developmental stability for variability and poor performance. Similarly, after infants finally acquire sufficient strength and control to maintain balance in an upright standing position, they experience an initial decrement in performance when they take their first walking steps a few weeks later.

The real-time process of gait initiation—taking the first step in a walking sequence—literally invites falling, but in this case, falling is deliberate and controlled. Walkers must deliberately induce disequilibrium to shift the body weight onto one foot and to produce the propulsive forces necessary to move the body forward (Breniere & Do, 1991; Breniere, Do, & Bousset, 1987; Ledebt, Bril, & Breniere, 1998). In adults, gait initiation begins before the swinging foot ever leaves the ground. First, in a preparatory phase that disrupts the equilibrium of the standing posture, the center of foot pressure moves backward toward the heels and sideways, first, slightly away then rapidly toward the standing foot (Breniere & Do, 1986; Breniere et al., 1987; Jian, Winter, Ishac, & Gilchrist, 1993). The change in foot pressure causes the center of mass to accelerate in the opposite direction: forward and toward the swinging foot. Next, in a takeoff phase, the swinging foot lifts from the ground and the total weight of the body is carried by the stance leg. Now, the body is falling forward and the velocity of the center of mass increases exponentially.

By the time that the swinging foot recontacts the ground, the center of gravity is moving at peak progression velocity (Breniere & Do, 1986; Breniere et al., 1987; Jian et al., 1993). At the end of the first step, the velocity is nearly at the steady state velocity of the entire walking sequence. How do walkers manage this? For faster intended walking speeds, adults lean their bodies farther forward by shifting their center of foot pressure farther backward (Breniere et al., 1987). As in sprinting, these actions build up more propulsive forces during the preparatory phase before the walker’s foot has left the ground. For slower intended speeds, adults exhibit less forward lean, and foot pressure exhibits a
smaller backward excursion. These findings are remarkable because they indicate an exquisite anticipation of the forces needed for the intended walking speed. Thus, for adults, the real-time process of gait initiation is loosely analogous to the developmental process of moving backward initially to facilitate forward progress eventually. In this case, the initial back step is beautifully coordinated with the size of the forward step.

For infants, the problem of gait initiation is somewhat different: Babies must cope with the two competing necessities of minimizing the disequilibrium inherent in their new upright posture and creating the disequilibrium required to move (Ledebt et al., 1998). In contrast to adults, infants do not initiate gait with a consistent backward and sideways displacement of their center of foot pressure prior to liftoff, and they do not show anticipation of their intended walking speed by building up the appropriate propulsive forces before the end of their first step (Breniere, Bril, & Fontaine, 1989). Instead, in the earliest days after walking onset, infants’ strategies for inducing disequilibrium and catching the body appear to be variable and idiosyncratic (Adolph, Vereijken, & Shrout, 2003; McCollum, Holroyd, & Castelfranco, 1995; McGraw, 1945). With a “falling” strategy, infants raise up on tiptoe and allow themselves to fall forward. With a “twisting” strategy, they wind their trunk like a spring and then let fly bringing their swinging leg around using the torque and angular momentum of the trunk. With a “stepping” strategy, they lift the swinging leg by bending the knee and minimize the fall by taking very small forward steps.

Adultlike anticipatory control of gait initiation takes years to acquire (Ledebt et al., 1998). After the first few months of walking, in the preparatory phase of gait initiation, infants apply vertical force with the swinging leg to load the standing leg and unload the swinging leg. They move the swinging leg forward by tilting the stance leg and pelvis sideways (Assaiante, Woollacott, & Amblard, 2000). As infants’ bodies begin to accelerate forward during the takeoff phase, the swinging foot reaches out to catch the body and infants simply control the fall as best they can. Even as the foot lifts, the pelvis drops on the side of the swinging leg as if infants’ bodies are collapsing downward into the fall (Bril & Breniere, 1993). Both before and after liftoff, infants’ legs, pelvis, trunk, and head oscillate more in sideways and front-back directions compared with preschool-age children and adults (Assaiante et al., 2000). At 4 years of age, children finally show a backward shift in the center of foot pressure and they achieve steady state velocity by the end of their first step, but the size of the backward shift is not yet correlated with walking velocity (Ledebt et al., 1998). At 6 years, the size of the preparatory backward displacement in foot pressure is correlated with walking velocity but is still not at adult levels.

**Fits and Starts**

In contrast to motor development where research has enjoyed a long history of tracking trajectories in individual children, microgenetic descriptions of physical growth are rare. The typical approach to studying body growth is to collect measurements from large cross-sectional samples or to measure children’s bodies longitudinally at quarterly or yearly intervals. Given the high variability between children at the same age and the relative paucity of data points for individual children at different ages, the typical analytic strategy is to average over children and interpolate between observations, mathematically smoothing out any jitter in the growth curve. Thus, as illustrated by the curve shown in Figure 4.3a, body growth is depicted as a smooth continuous function. From birth to adulthood, the standard growth curve has three bends caused by a rapidly decelerating rate of growth over infancy, a relatively slow but constant rate of growth during middle childhood, and the pubertal growth spurt prior to reaching final adult size (e.g., Tanner, 1990).

Microgenetic descriptions of physical growth in individual children provide a very different picture of development. As illustrated in Figure 4.3b, actual growth spurts bear no resemblance to the mathematically smoothed bump on the standard growth curve that represents researchers’ traditional view of the adolescent growth spurt. Children’s growth is episodic, not continuous (M. L. Johnson, Veldhuis, & Lampl, 1996; Lampl, 1993; Lampl et al., 2001; Lampl & Johnson, 1993; Lampl, Veldhuis, & Johnson, 1992). Brief periods (24 hours) of extremely rapid growth are interspersed with long periods of stasis during which no growth occurs for days or weeks on end. Episodic development is characteristic of changes in height, weight, head circumference, and leg bone growth and of every period of development—fetal (Lampl & Jeanty, 2003), infancy (Lampl, 1993; Lampl & Emde, 1983), middle childhood (Lampl, Ashizawa, Kawabata, & Johnson, 1998; Togo & Togo, 1982), and adolescence (Lampl & Johnson, 1993; Togo & Togo, 1982). When measured daily, infants’ height increased by 0.5 to 1.65 cm punctuated by 2- to
Figure 4.3 Growth curves for height. (a) Standard growth curves from birth to 18 years. Data are mathematically smoothed and averaged over children. Dashed line represents boys. Solid line represents girls. Source: From growth charts developed by the National Center for Health Statistics in collaboration with the National Center for Chronic Disease Prevention and Health Promotion (2000). (b) Microgenetic episodic growth curve for one exemplar infant. Each vertical line represents daily replicate observations. Source: From “Saltation and Stasis: A Model of Human Growth,” by M. Lampl, J. D. Veldhuis, and M. L. Johnson, 1992, Science, 258, pp. 801–803. Reprinted with permission.

28-day periods of no growth (Lampl et al., 1992). Sampling at weekly intervals preserved the episodic nature of children’s growth but had the effect of reducing the number of growth spurts, increasing the amplitude of the spurts, and increasing the periods of stasis (e.g., for infants observed at weekly intervals, height increased by 0.5 to 2.5 cm interspersed by 7- to 63-day periods of no growth). Although episodic growth characterized every child measured, the timing of spurts, the size of the growth increments, and the length of the plateaus showed large intra- and intersubject variability.

Even within a 24-hour period, growth is not continuous. Children appear to grow more at night while lying down than during the day while standing and walking, especially in their weight-bearing extremities (Lampl, 1992; Noonan et al., 2004). For years, pediatricians assumed a link between nighttime growth and nighttime lower leg pains, but there were no data to corroborate speculations about the source of children’s “growing pains.” In a recent tour de force of micromeasurement, researchers collected direct measures of lower leg bone growth at 3-minute intervals over a 3-week period via microtransducers implanted into the tibia bones of 3 free-ranging lambs (Noonan et al., 2004). Video recordings synchronized with the activity of the microtransducers specified the lambs’ activities during periods of growth and stasis. Approximately 90% of all growth occurred while the lambs were lying down. Weight bearing while standing or walking resulted in biomechanical compression of the growth plate cartilage.

Evidence for Developmental Stages

The dramatic example of body growth shows how inadequate sampling intervals can lead researchers to mischaracterize the underlying developmental trajectory. If the sampling interval is too large, findings will be insensitive to important fluctuations in the data. Skills that are indexed with interval data (such as height and weight) will appear continuous regardless of whether the underlying trajectory is episodic or U-shaped. Skills that are indexed with binary data (such as object permanence and conservation of quantities) will look stage-like regardless of whether the actual trajectory is variable. The risk is that erroneous descriptions of development can compromise theorizing about underlying mechanisms. Given the expense of collecting increasingly microscopic observations, researchers need to know how small is small enough to capture the essential shape of change.

To answer this question, Adolph and colleagues (Adolph, Robinson, Young, & Gill-Alvarez, 2005; Young, Webster, Robinson, Adolph, & Kanani, 2003) sampled 32 infant motor skills (rolling, sitting, crawling, cruising, walking, etc.) from 11 infants on a daily basis using a
checklist diary with parents as the informants. The period of observation averaged 13 months per child. Due to missing data and skills, 261 time series were available. Of these, only 42 time series (16%) showed single stage-like developmental transitions. In these cases, infants never demonstrated the skill prior to the onset day and always demonstrated the skill after the onset day. In the other 84% of the time series, trajectories were variable. Skills sputtered in and out of infants’ repertoires, with 3 to 72 transitions between skill absence and presence. In these cases, the selection of an onset day is arbitrary because an infant might walk on Monday, but not again until Thursday, and then not again until the following week, and so on. The data argue against the widely held practice of using punctate estimates of onset dates in normative screening tests (e.g., Frankenburg & Dodds, 1967) and in estimates of infants’ motor experience (e.g., Adolph et al., 2003; Bril & Ledebt, 1998; Campos et al., 2000).

Most important, the consequence of sampling at intervals larger than a single day was a dramatic loss of sensitivity to detect the variability in the data (Adolph, Robinson, et al., 2005; Young et al., 2003). Sampling at 2- to 30-day intervals was simulated by systematically removing observations, then reconstructing the developmental trajectories based on the reduced number of observations. The resulting data set included the original data (1-day interval) and the sum of the 2- to 30-day simulated intervals by phase multiplied by the original 261 available time series for a total of 129,456 time series. Of these, 109,120 were variable.

Loss of sensitivity followed an inverse power function (visualize a curve with a sharp initial drop-off that slowly tapers toward 0 over an extended tail). For each day that widened the sampling interval, the loss of sensitivity increased at a greater rate. At the simulated sampling frequency of once per week (considered heroic in microgenetic studies of motor skill acquisition), 51% of the variable time series erroneously appeared stagelike. At the simulated rate of once per month, 91% of the variable time series appeared stagelike. In other words, stagelike developmental trajectories may be an artifact of inadequate sampling rather than a true description of the underlying course of development.

**Variability**

Traditionally, researchers in cognitive and perceptual development viewed variability as error variance to be minimized or stochastic noise to be ignored. Currently, however, variability is enjoying a sort of renaissance in these areas, where researchers have begun to recognize change in variability as an important marker of learning and development (e.g., Siegler, 1994, 1996; Siegler & Munakata, 1993). For example, while learning new strategies to solve math, matrix completion, and conservation of quantity problems, children show a spike in variability between erroneous and correct ways of thinking (Alibali, 1999; Goldin-Meadow, Alibali, & Church, 1993).

In contrast to the long disregard of variability in cognitive and perceptual development, researchers in motor development and motor learning have a tradition of using measures of real-time variability (e.g., the standard deviation, coefficient of variation, or category counts) as dependent variables to index learning and development in motor skill acquisition (e.g., Adolph et al., 2003; J. E. Clark et al., 1988; Vereijken, van Emmerick, Whiting, & Newell, 1993). The movements of infants and novices are notoriously variable and unreliable, whereas movements of adults and experts are typically smooth and consistent.

**Crawling**

Prior to crawling on hands and knees, many infants belly crawl with their abdomen resting on the floor for at least part of each cycle. Even excluding solutions wherein infants hitch along sitting, crab on their backs, and log roll, belly crawling may be the most variable, idiosyncratic, and creative of all infants’ motor skills (McGraw, 1945). Infants use their arms, legs, chests, bellies, and heads in various combinations, sometimes pushing with only one limb in a girdle and dragging the lame limb behind, sometimes ignoring both arms and scraping along with the cheek on the floor or dragging both legs like a marine, sometimes pushing with first the knee then the foot on one leg, sometimes launching themselves from knees or feet onto the belly, and so on (Adolph et al., 1998; Gesell, 1946; Gesell & Ames, 1940). Even when all four limbs move, patterns of interlimb timing are variable (Adolph et al., 1998; Freedland & Bertenthal, 1994). Infants move ipsilateral limbs together like goose-stepping, move arms and legs on alternate sides of the body together like a trot, lift front then back limbs like a bunny hop, and lift all four limbs into the air at once like a swim. Belly crawling is so variable that infants change the configuration of limbs used for support and propulsion and the timing between limbs from cycle to cycle (Adolph et al., 1998). Variability in belly crawling is all the more striking because infants show a dra-
matic decrease in the variability of interlimb timing within a week or two of crawling on hands and knees (Adolph et al., 1998; Freedland & Bertenthal, 1994).

**Reasons for Variability**

What can we make of such variability? With the new renaissance of variability in developmental psychology, researchers in motor development have begun to herald variability as a causal agent of change rather than merely a marker or correlate (e.g., Bertenthal, 1999; Goldfield, 1995; Goldfield, Kay, & Warren, 1993). Indeed, Freedland and Bertenthal (1994, p. 31) wrote with regard to belly and hands-knees crawling, “Variability in performance is one of the driving forces for the emergence of new behaviors.” Changes in variability around real-time transitions illustrate researchers’ shift from describing changes in variability to treating variability as a causal mechanism. In Kelso’s (1995) classic task, adults point both index fingers first to the right then to the left. At slow speeds, variability in the coordination between the two fingers is low. As participants try to wiggle their fingers back and forth at faster and faster speeds, variability increases until the fingers shift to an in-out pattern, at which point variability sharply decreases. On some accounts, the loss of stability is the chief mechanism that causes such changes in behavioral patterns (Bertenthal, 1999; Spencer & Schöner, 2003; Zanone et al., 1993). That is, variability is a prerequisite for any change between stable states, whether in real time, over the course of learning, or over development.

A second current conceptualization of behavioral variability concerns its exploratory function. On analogy to the evolutionary process of variability and selection and the neural process of overproduction and pruning, some researchers view variability as providing the fodder for subsequent selection and sculpting based on feedback from ongoing movements (e.g., Bertenthal & Clifton, 1998; Berthier et al., 2005; E. J. Gibson & Pick, 2000; Thelen & Smith, 1994). On this view, variable belly crawling steps (Bertenthal, 1999; Freedland & Bertenthal, 1994), arm flaps (Thelen et al., 1993), leg kicks (Thelen & Fisher, 1983a), and so on could create the raw materials for more efficient movements by generating an information-rich array of possibilities.

Of course, important exploratory functions could arise as a developmental by-product of variability (Adolph, 1997), just as many important physiological and behavioral forms can be evolutionary exaptations—characters that evolved for other uses or no function at all that were co-opted later for their current role (Gould & Vrba, 1982). However, many researchers portray variability in infants’ movements as intentional exploration motivated by a search for information (e.g., Bertenthal & Clifton, 1998; Goldfield, 1995; von Hofsten, 1997). Furthermore, in some cases, variability is viewed as both an active search for alternatives and as an impetus for exploration: Inconsistency in performance impels infants to explore alternative behaviors until they settle on a more efficient solution (Freedland & Bertenthal, 1994; Goldfield, 1995).

Although new views of variability have stimulated thinking and research, some of the proposals are problematic. The problem with imbuing variability in skills like crawling and reaching with intent is that the evidence for intentional exploration and active searching is simply the finding of variability itself. The problem with treating variability as an independent variable, moderator, or mediator—a causal prerequisite for learning and development—is that variability can also serve as a dependent variable for explaining the same phenomena. Natural selection may not be a useful metaphor in every case of behavioral development (just as evolution may include multiple mechanisms such as exaptation and spontaneous mutation) and generalizations from simple laboratory tasks such as finger-wiggling may not always hold true.

Belly crawlers show no evidence of selection or pruning and no evidence of a sudden spike in variability around the transition to crawling on hands and knees (Adolph et al., 1998). Rather, infants showed improvements in speed and proficiency despite unabated variability over weeks of belly crawling, and nearly every infant used an alternating gait pattern to crawl on hands and knees regardless of whether they had previously crawled on their bellies. Without a salient cost to performance, variability may continue unabated (Vereijken & Adolph, 1999). Perhaps the safest conclusion is that development is a many-splendored thing and variability may play multiple roles in the developmental process (see Siegler, Chapter 11, this Handbook, this volume). Frequently, changes in variability inform on that process, but sometimes variability may simply reflect noise.

**Time, Age, and Experience**

Development is about change over time. Thus, a central question for developmental psychologists is how best to conceptualize the passing of time and the factors that accompany it (e.g., Wohlwill, 1970). How should we order repeated observations and assign participants into
groups? The most common solution is to put children's chronological age at the time of testing on the x-axis. Indeed, many researchers do not consider a study to be developmental without comparisons between age groups. The most common alternative is to retain the regularity of days, weeks, months, and so on, but to normalize observations and subject groupings by children's experience, calculated with reference to an estimated day of skill onset (e.g., Adolph et al., 1998; Bertenthal, Campos, & Kermoian, 1994; Bril & Breniere, 1992; Corbetta & Bojczyk, 2002). Thus, instead of comparing individuals at 3 and 6 months of age or comparing groups of 3- and 6-month-olds, researchers might compare children over the first few months of reaching or the first few years of walking. Similar research strategies include retaining the serial order of milestone events (e.g., standers, new walkers, experienced walkers, runners) without retaining the interval spacing (e.g., Sundernier, Woollacott, Roncesvalles, & Jensen, 2001; Witherington et al., 2002) and holding age constant while varying experience with particular motor skills (e.g., Adolph, 2000; Campos et al., 2000). Here, we focus on the development of walking to illustrate some of the issues involved in representing, describing, and explaining change over time.

**Improvements in Walking Skill**

After 75 years or so of research on the development of walking, researchers have compiled a consistent constellation of related parameters that change with age and experience. Between 10 and 16 months of age, most infants take their first independent walking steps (Adolph et al., 2003; Frankenbarg & Dodds, 1967). Initially, infants have such difficulty surmounting the dual problems of balance and propulsion that their walking gait resembles that of Charlie Chaplin. They take small forward steps with their legs splayed wide from side to side (e.g., Adolph et al., 2003; Bril & Breniere, 1992; Burnett & Johnson, 1971; McGraw, 1945; Shirley, 1931). Their hips are externally rotated and their toes point out to the sides to further increase the base of support (e.g., Adolph, 1995; Ledebt, van Wieringen, & Savelbergh, 2004). They co-contract extensor and flexor muscles in their legs (Okamoto & Goto, 1985) and their excessively bent knees fail to cushion the downward fall at foot contact and fail to extend the leg fully at toe-off (Sutherland, Olshen, Cooper, & Woo, 1980). They spend a relatively long time with both feet on the ground and a relatively short time with one foot swinging through the air (e.g., Bril & Breniere, 1989, 1991, 1993); as a consequence, overall progression velocity is slow, step frequency is high, and infants land flat-footed or on their toes because there is no time for them to dorsiflex their ankles (McGraw, 1940; Thelen, Bril, & Breniere, 1992). The time and distance of each step is variable and asymmetrical, suggesting that infants are recovering balance from step to step (Adolph et al., 2003; J. E. Clark et al., 1988; J. E. Clark & Phillips, 1987; Ledebt et al., 2004; McGraw & Breeze, 1941). New walkers hold their arms stationary in a high-guard position, with elbows bent, palms turned up, and hands raised above waist level (Ledebt, 2000; McGraw, 1940). Their heads and trunks wobble up and down and from side to side (Bril & Ledebt, 1998; Ledebt, Bril, & Wiener-Vacher, 1995). Most telling, the vertical acceleration of infants' center of gravity is negative at foot contact, meaning that babies are falling downward rather than propelling forward during periods of single leg support (Bril & Breniere, 1993).

Figure 4.4 shows the characteristic time course and direction of improvements in walking skill over infancy and early childhood. The base of support narrows as infants take longer steps with their legs closer together laterally and their toes pointed more straight ahead (e.g., Adolph et al., 2003; Bril & Breniere, 1992). Muscle actions become more reciprocal (Okamoto & Goto, 1985) and steps appear less jarring and variable (e.g., J. E. Clark et al., 1988; Ledebt et al., 2004). As the relative duration of double support decreases and single support increases, walking speed increases and infants land on their heel at foot contact (Bril & Breniere, 1989, 1991, 1993; Thelen et al., 1992). Arms lower toward infants' sides and begin to swing in alternation with leg movements (Ledebt, 2000). Infants stabilize the pitch and roll of their head and trunk (Ledebt et al., 1995) by rigidly locking their upper body parts together "en bloc" (Assaiante, 1998). Eventually, children unlock the rigid coupling between the head and trunk and begin to coordinate the pitch and roll of the head with the reactive up/down and sideways movements of the body caused by each walking step (Assaiante, Thomachot, Aurenty, & Amblard, 1998; Bril & Ledebt, 1998). The size of the negative value of the vertical acceleration of the center of gravity at foot contact slowly decreases until the sign of the function finally becomes positive as in adult walkers (Bril & Breniere, 1993). At this point, when children can “push off” during single leg support,
they have finally mastered control over both balance and disequilibrium.

Since the 1930s, researchers have shared widespread agreement about the proximal cause of the characteristic improvements in walking skill: Infants must acquire sufficient muscle strength to propel their bodies forward while supporting their body weight on one leg and sufficient postural control to maintain balance, especially during periods of single limb support (e.g., Bril & Breniere, 1993; Bril & Ledeht, 1998; McGraw, 1945; Thelen, 1984a). Where most modern and early researchers diverge concerns their assumptions about the distal source of improvement in the development of walking—the factors that drive increases in muscle strength and balance control. The early pioneers plotted developmental changes in walking skill with infants’ age on the x-axis to emphasize the role of neural maturation and body growth in facilitating improvements. In contrast, most modern researchers plot similar graphs with infants’ walking experience on the x-axis to emphasize the role of learning and practice.

Given the 6-month range in infants’ age at walking onset, normalizing the data to children’s walking onset age rather than their birth date facilitates graphical and
statistical comparisons between children (e.g., Bril & Breniere, 1993; Bril & Ledebt, 1998; J. E. Clark et al., 1988; Corbetta & Bojczyk, 2002). Note, for representing and describing change in individual infants, age and experience are equivalent measures. In addition, formal statistical models comparing the respective roles of infants’ walking experience, chronological age, and body dimensions show that only walking experience explains unique variance in skill improvement over the first 2 years of life (Adolph et al., 2003; cf., Kingsnorth & Schmuckler, 2000). Over the next several years, developmental milestones are a more sensitive measure of improvements than age (Sundermier et al., 2001).

Moreover, as illustrated in Figure 4.4, for many measures, the development of walking skill resembles the negatively accelerated performance curves found in most motor learning tasks (Schmidt & Lee, 1999): Initial improvements are rapid and dramatic while subsequent improvements are more gradual and subtle. Most researchers identify the elbow in the rate of change at 3 to 6 months after walking onset (e.g., Adolph et al., 2003; Bril & Breniere, 1992, 1993; Bril & Ledebt, 1998; McGraw, 1945). Analogous to motor-learning tasks, the initial phase where the performance curve is steepest may reflect infants’ struggle to discover the relevant parameters that allow forward progression and balance. The subsequent period of more gradual change may reflect a process of honing and fine-tuning the values of the gait parameters to maximize the biomechanical efficiency of walking.

**Empty Time**

Regardless of the relative predictive power of children’s chronological age versus their walking experience, neither factor alone or in combination provides an explanation for the improvements in children’s walking skill. The widespread use of age and experience as predictor variables in analysis of variance and regression analyses imbues these factors with the causal quality of independent variables (Wohlwill, 1970). However, they are not. Children are not randomly assigned to age or experience groups and each child is (or will be) a member of every group (e.g., in contrast to ethnic and sex groups). Cohort effects and cultural differences are well documented in the development of walking (e.g., Hopkins & Westra, 1990; Super, 1976). In addition, time could just as easily be the dependent measure, as typified by the common use of trials to criterion and time on task as dependent variables in motor-learning studies (Schmidt & Lee, 1999). Most problematic, the passing of time since infants’ birth date or date of walking onset is merely a convenient proxy for age- or experience-related factors that are currently unspecified or difficult to measure. In Wohlwill’s (1970) harsh assessment, time itself is conceptually empty. It serves as a “cloak for ignorance” (p. 50).

Rather than relying on age as a crude stand-in for developmental changes in infants’ brains and body dimensions, a more optimal research strategy would be to measure the putative causal factors and correlates more directly. For example, the frontal lobes show a temporary surge of electroencephalogram (EEG) activity in the first few weeks of crawling (Bell & Fox, 1996), consistent with an initial overproduction and subsequent pruning in neural connections. The otolith channel of the vestibular-ocular reflex shows a sharp increase in sensitivity to linear accelerations at the time of walking onset (Wiener-Vacher, Ledebt, & Bril, 1996), linking the ability to stabilize gaze while the head moves with the onset of an activity that accelerates the head through space. The natural slimming-down of infants’ body proportions is correlated with improvements in walking skill (e.g., Adolph, 1997; Shirley, 1931) and more babyish top-heavy proportions (experimentally induced with lead-weighted shoulder packs or platform shoes) result in decrements to walking skill (Adolph & Avolio, 2000; GarciaGuirre & Adolph, 2005a; Schmuckler, 1993; Vereijken, Pedersen, & Storksen, 2005; Yanez, Domakonda, Gill-Alvarez, Adolph, & Vereijken, 2004), suggesting that biomechanical constraints affect strength and balance.

**What Infants Experience**

Just as age is only a crude stand-in for unspecified developmental changes, the number of days since walking onset is only a proxy for practice and exposure. Researchers rely on locomotor experience as a causal factor in development for a range of psychological domains (e.g., Bertenthal et al., 1994; Campos et al., 2000). However, the construct of locomotor experience is largely unexamined. Ironically, the abundance of laboratory data collected over the past 100 years with infants walking short straight paths on flat ground under conditions of steady state velocity cannot speak to the quantity or content of infants’ everyday experiences with balance and locomotion. In everyday life, infants travel along
circuitous paths for large distances over variable ground surfaces with variable walking speeds.

In particular, daily checklist diaries, “step-counters” in infants’ shoes, and video recordings of infants walking in everyday environments reveal large individual differences in the amount of practice that infants acquire with walking and large fluctuations for individuals across situations and days (Adolph, 2002, 2005; Adolph, Robinson, et al., 2005; Chan, Biancaniello, Adolph, & Marin, 2000; Chan, Lu, Marin, & Adolph, 1999; Garcia-aguirre & Adolph, 2005b). Many infants walk intermittently in the first several weeks after onset, vacillating between days when they walk and days when they do not (Adolph, Robinson, et al., 2005). Within days, walking experience is distributed in bouts of activity interspersed with periods of quiet stance when infants stop to play, manipulate objects, or interact with a caregiver (Garcia-aguirre & Adolph, 2005b). During trips toward a distant destination (on a city sidewalk with a caregiver), bouts tend to be longer in duration ($M = 18$ s) and contain more consecutive steps ($M = 45$ steps) than during free play where destinations are more transient and caregivers are less likely to encourage infants to walk ($M_{bou}t$ length = $5$ s, $M_{steps} = 11$).

Accumulated over the course of a normal waking day, the quantity and variety of infants’ experience is truly massive (e.g., Adolph, 2002, 2005; Adolph et al., 2003). Each day, infants take more than 9,000 steps and travel the distance of more than 29 football fields. They travel over nearly a dozen different indoor and outdoor surfaces varying in friction, rigidity, and texture. They visit nearly every room in their homes and they engage in balance and locomotion in the context of varied activities. Minor inconsequential falls are common, averaging 15 times per hour, but serious falls that cause infants to engage in sustained crying or that result in minor injuries occur less than once per month (Garcia-aguirre & Adolph, 2005b).

In sum, infants’ everyday walking experiences resemble a type of practice regimen that would be highly conducive to motor learning: massive amounts of variable and distributed practice largely free from aversive consequences for errors (Gentile, 2000; Schmidt & Lee, 1999). However, practice is not doled out evenly across infants and days and researchers have not yet linked the various features of infants’ practice regimen with improvements in walking skill. Thus, to infuse the construct of locomotor experience with conceptually meaningful content, researchers might quantify practice or exposure by putting the number of walking steps, number of walking bouts, distance traveled, duration of time engaged in balance and locomotion, number of surfaces traversed, number of falls, or the like on the x-axis instead of simply counting the number of elapsed days since walking onset.

Movement Is Ubiquitous

Movement is perhaps the most ubiquitous, pervasive, and fundamental of all psychological activity. It is the hallmark of animacy and the essence of agency. Across development, self-initiated movements of the eyes, head, limbs, and body provide the largest source of infants’ perceptual experiences.

Epochs of Movement

As illustrated in the case of walking, the sheer quantity of infants’ experiences with movement is staggering. By the time that infants begin to show visual expectancies in laboratory tasks at 3.5 months of age, they may have performed 3 to 6 million eye movements outside the laboratory and viewed countless examples of occlusion and other visual events (Haith, Hazan, & Goodman, 1988; S. P. Johnson, Slemmer, & Amso, 2004). By the time that children succeed at spatial search tasks at 10 months of age, they have likely accumulated enough crawling steps to travel more than half the length of Manhattan (Adolph, 2005). By the time that infants are 12 months old, they have likely experienced over 110,000 bouts of wiggles, waves, kicks, and flaps of 47 different types of spontaneous rhythmical stereotyries in their legs, arms, heads, and trunks (Thelen, 1979, 1981b). The connectionist notion of “epochs” of experience (Munakata, McClelland, Johnson, & Siegler, 1997) is the appropriate metric for measuring the quantity of infants’ movement.

The vast quantity of experience, however, does not imply an unremitting march. The bursts and bouts of infants’ movements wax and wane with daily sleep/wake cycles and the acquisition of new motor skills. Although newborns are asleep most of the day, they are still moving (e.g., Erkinjuntti, 1988; Fukura & Ishihara, 1997). Sleeping movements include gross movements of the limbs and trunk together, localized movements of one limb, and fast twitches (Fukumoto, Mochizuki, Takeshi, Nomura, & Segawa, 1981). Waking movements are more
frequent and of higher amplitude, shifting from slow, writhing movements due to excessive co-contractions in the first weeks of life to smaller, more graceful, and purling fidgety movements between 8 and 12 weeks of life (Cioni, Ferrari, & Prechtl, 1989; Hadders-Algra & Prechtl, 1992; Hadders-Algra, van Eykern, Klip-Vanden Nieuwendijk, & Prechtl, 1992; Prechtl & Hopkins, 1986). Rhythmic stereotypes are apparent from the 1st month of life and are most common when infants are awake and aroused but not crying (Thelen, 1979, 1981b). Peak frequencies of particular stereotypes coincide with the acquisition of new motor skills (e.g., kicking and rocking appear prior to crawling, waving the arms appears prior to reaching, and swaying appears prior to independent standing; Gesell & Thompson, 1934; McGraw, 1945; Spencer et al., 2000; Thelen, 1996).

Movement Is Pervasive in Development

From the very beginning of life, movement is a pervasive feature of development. Fetuses’ first spontaneous self-produced movements appear somewhere between 5 and 6 weeks after conception, within a few days after fetuses develop body parts to move (Moore & Persaud, 1993). The earliest movements are tiny, barely discernible head bends and back arches (e.g., deVries et al., 1982; Nilsson & Hamberger, 1990; Prechtl, 1985). At 6 to 7 weeks postconception, fetuses slowly wave their limbs (deVries et al., 1982; Sparling & Wilhelm, 1993) and display quick, general startle movements, beginning in the limbs and radiating to the neck and trunk (deVries et al., 1982). Between 7 and 10 weeks postconception, limb waves and body bends become larger and more rapid and forceful (deVries et al., 1982). In addition, fetuses begin moving their arms and legs separately from the rest of their bodies, bend their heads up and down, turn their heads from side to side, open their mouths, hiccup, and bring their hands to their faces (deVries et al., 1982; Sparling, van Tol, & Chescscher, 1999). They begin to execute their first “breathing” movements, moving their diaphragm and abdomen in and out to draw small amounts of amniotic fluid in and out of the lungs (James, Pillai, & Smoleniec, 1995; Pillai & James, 1990).

Starting at 12 weeks after conception, two thirds of fetuses’ arm movements are directed toward objects in the uterus—their own faces and bodies, the wall of the uterus, and the umbilical cord (Sparling et al., 1999). Many hand-to-body and hand-to-object movements occur in brief bouts of activity (Sparling et al., 1999), like fetal versions of Piaget’s (1952) primary and secondary circular reactions. By 13 weeks after conception, the fetal movement repertoire has expanded to more than 16 different types of movements including whole body stretching, alternating leg movements, somersaults, yawns, sucking, and swallowing of the amniotic fluid through the nose and mouth (Cosmi, Anceschi, Cosmi, Piazze, & La Torre, 2003; deVries et al., 1982; Dogtrop, Ubels, & Nijhuis, 1990; James et al., 1995; Kuno et al., 2001; Nilsson & Hamberger, 1990; Pillai & James, 1990). By 16 weeks, fetuses’ hands can find their mouths so that they can suck their thumbs (Hepper, Shahidullah, & White, 1991). Fetuses begin moving their eyes even before the lids unfuse at 26 weeks (Dogtrop et al., 1990; Moore & Persaud, 1993; Prechtl & Nijhuis, 1983).

Fetal activities follow a daily rhythm, increasing during the evening and decreasing in early morning (Arduini, Rizzo, & Romanini, 1995). Across weeks of gestation, whole body movements and large movements of the arms and legs peak at 14 to 16 weeks postconception, averaging nearly 60% of each observation, then begin to decrease as fetuses’ growing bodies occupy increasingly more space in the uterus (D’Elia, Pighetti, Moccia, & Santangelo, 2001; Kuno et al., 2001). By 37 weeks or so, fetuses are so cramped that their hands are often molded to the shape of their heads with the back of their hands pressed against the uterine wall (Sparling et al., 1999).

Movement Is Fundamental

Movements are not only omnipresent in development, they are literally as basic to life as breathing. Drawing air into the lungs requires movement of the diaphragm and intercostal muscles to expand the chest cavity (Goss, 1973; Marieb, 1995). After infants’ first dramatic breaths at birth, breathing movements typically fade into the background of most researchers’ awareness. Breathing, however, must be actively controlled when it occurs in conjunction with other movements, as when adults control their breathing movements during meditation, swimming, late stages of labor, and so on.

Like breathing, the seemingly simple acts of swallowing and sucking are often taken for granted. Although fetuses have ample practice exercising the muscles and body parts used for breathing and swallowing, fetuses do not breathe air and the two types of movements do not need to be coordinated (J. L. Miller,
In contrast, after birth, the anatomy of the body requires that breathing and swallowing movements be staggered in time so that infants do not get gas pains from ingesting air or choke from aspirating milk. Initially, milk and air share the same passage as they enter the body through the pharynx, but milk must divert to the esophagus and air to the trachea.

Sucking also begins prenatally (Humphrey, 1970). After birth, infants suck to feed and they display non-nutritive sucking movements while sleeping or sucking a finger or pacifier (Wolff, 1987). Although sucking is possible while breathing, healthy term infants most frequently stagger non-nutritive sucking and breathing movements with a complex 3:2 ratio of sucks to breaths (Goldfield, Wolff, & Schmidt, 1999a, 1999b). The sophisticated temporal coordination between breathing, swallowing, and sucking movements is highlighted when infants have problems feeding (Craig & Lee, 1999). When coordination breaks down, breathing is typically the bottleneck (van der Meer, Holden, & van der Weel, in press). The need to breathe competes with the need to swallow (Goldfield, 2005). Premature infants are especially at risk for feeding problems, in part because it is difficult for them to regulate their breathing. Thus, they cannot coordinate the sucking, breathing, and swallowing movements required for feeding (Goldfield, 2005). For example, at 32 weeks postconception, preterm infants stop breathing for a few moments before and after each swallow (Mizuno & Ueda, 2003). The pauses allow infants to feed without choking on the milk, but they also result in insufficient amounts of oxygen while feeding. Like full term infants, by 35 weeks postconception, preterm infants can intersperse their swallows between the parts of a breath, swallowing between breathing out and breathing in (Mizuno & Ueda, 2003; van der Meer et al., in press).

During nursing, as milk flow increases, so too do sucking and swallowing. Milk accumulates in the mouth after several bursts of sucking, then it is swallowed. Additional swallows clear any residual milk left in the mouth (Newman, Keckley, et al., 2001). In addition to coordinating these movements during nursing, infants also change the ratios of sucking and swallowing to breathing over the course of a feeding session as they become satiated and the intensity of their sucking decreases (Goldfield, Richardson, Saltzman, Lee, & Marggets, 2005). When milk delivery is accommodated to premature infants’ irregular breathing patterns (with a cleverly instrumented bottle system), premature infants can better coordinate breathing, sucking, and swallowing to feed more effectively (Goldfield, 2005).

Summary: Models of Change

How might the details of infant sucking, wiggling, crawling, walking, kicking, and so on pertain to psychological research outside the domain of motor development? At a time when so much of the work in developmental journals consists of developmentally atheoretical descriptions or narrow developmental theories about highly specialized phenomena, an effort to extract general principles of development seems an important and refreshing enterprise (E. J. Gibson, 1994; Siegler & Munakata, 1993; Thelen & Smith, 1994). Indeed, Gesell’s most important and enduring legacy may be his example of using the formal structure of infants’ movements as a model system for understanding general principles of developmental change. With the case studies in this section, we provided the flavor of a model system approach to motor development by describing how researchers have used changes in the temporal structure and spatial configuration of infants’ movements to address some of the big issues that all developmental psychologists must face: Can development create qualitatively new forms? What causes development to emerge? What is the role of variability in performance? How can we determine the shape of a developmental trajectory? How should we understand the passage of time? And, how ubiquitous is the stuff of development?

Thelen and Bates (2003) affirmed in a recent special issue on dynamic systems and connectionism their belief “that there are general principles of development: mechanisms and processes that hold true whatever the content domain” (p. 378). In motor development, Thelen’s influential work stands as a testament to the effort to discover such general principles and to construct a unified dynamic systems approach to development (Thelen, 1995; Thelen et al., 2001; Thelen & Smith, 1994, 1998; Thelen & Ulrich, 1991). Dynamic systems may prove to be a grand unifying theory of development or it may not. Our guess is that any single approach may prove to be too limiting or too specious to do justice to the many guises that development takes and to the many issues that are raised by developmental research. However, without the effort to transcend the particulars of a phenomenon or a content domain, researchers will never
establish a science of development. Our aim in this section was to illustrate how a small, clear, specialized model system can be used to investigate large, complex, general issues in development. Moreover, the transparent nature of infants' movements nested over multiple time scales provides a uniquely tractable and generative model system for undertaking the enterprise of developmental science.

MOTOR DEVELOPMENT AS A PERCEPTION-ACTION SYSTEM

In contrast to movements, actions, by definition, imply intentionality and a goal (Pick, 1989; Reed, 1982). Whereas infants' rhythmical leg kicks and arm flaps may be a by-product of arousal or random neural activity, infants' actions on objects and surfaces are intentional and purposeful. Whereas spontaneous movements may serendipitously create functional outcomes, actions are goal-directed from the outset and are expressly performed to serve an immediate function. The speed at which 10-month-olds reach for a ball, for example, depends on whether their goal is to fit the ball into a tube or to toss it into a tub (Claxton, Keen, & McCarty, 2003). Each part of the action anticipates the next part and is geared toward the final destination.

Satisfying goals through action requires animals to detect affordances, select among them, and sometimes create new possibilities for action. Behavior must be flexibly adapted to the local conditions. Povinelli and Cant's (1995) description of primate locomotion through the jungle canopy provides a wonderful example. Long-tailed macaques are so lightweight that they can safely ignore the strength and compliance of the arboreal support surface. They travel along the tops of branches and vines on all fours like squirrels, stepping over small gaps between supports and leaping over large ones. Siamangs are a bit heavier. They circumvent falling by suspending themselves below the canopy and swinging along from arm to arm. They judge the distance between branches and vines in terms of their arm length and the boost provided by a springy branch and the inertia of their swing. Orangutans are so heavy—the size of a large man—that the strength and the compliance of each branch are of crucial importance. They solve the problem of locomotion through the canopy by distributing their body weight over multiple supports, testing each branch and vine before shifting their weight, and bridging the gaps between neighboring supports by bending a tapering tree trunk under their weight until grasping a branch on the far side.

Like primate locomotion, the case studies in this section exemplify the issues involved in realizing affordances for action. The starting assumption is that adaptive actions are always goal directed and always embodied and contextually embedded. As described in the previous section, infants walking over a straight, flat path at steady state velocity provide a wonderfully rich paradigm for analyzing the formal structure of gait patterns. However, as frustrated researchers quickly learn when they try to elicit steady state velocity from toddlers over repeated trials, infants usually have different goals in mind: Infants alter their own functional body dimensions by holding their arms out and carrying toys; they stop and start to investigate a detail of the testing walkway; they accelerate to run into their parents' open arms. Thus, researchers who study motor development as a perception-action system focus on infants' ability to achieve their goals by detecting and adapting to changes in their physical propensities and surrounding environments. Researchers vary the available perceptual information by experimentally manipulating infants' functional body dimensions and level of balance control, altering the properties of target objects and surfaces, and providing infants with various types of social support for action.

We begin this section with the prospective, future-oriented nature of goal-directed looking and reaching and describe how even the simplest movements of the eyes, head, trunk, and extremities require infants to anticipate disruptions to a stable postural base. We use infants' responses to challenging ground surfaces to illustrate both flexibility and specificity in learning to detect affordances for action and we describe how exploratory movements provide the perceptual basis for guiding actions. We conclude this section with examples of how tools create new possibilities for action.

Prospective Control

The development of action is basically a matter of increasing prospective control: preparing and guiding actions into the future (von Hofsten, 1993, 1997, 2003, 2004). Time only runs in one direction. Thus, the only part of an action that can be controlled is the part that has not yet happened (von Hofsten, 2003). Reactive responding is only a method of last resort. In the worst
case scenario, actions are irreversible and reactive responses result in dire consequences (trips, slips, collisions, falling from the jungle canopy). In the best case scenario, reactive post hoc corrections cause actions to be jerky and inefficient because of the neural time lag in transmitting information through the body and the mechanical time lag in getting the various body parts to move. Perceptual information links time past with time future by using feedback from just prior movements to anticipate the consequences of future actions and by using updates from recent perceptual events to predict what will happen next. Perception provides a time bubble to continually extend action into the future, like a protective cushion between the body and its surrounds.

**Early Action Systems**

Infants’ looking behaviors are so frequently used to make inferences about perceptual and cognitive processes that developmental psychologists sometimes forget that the visual system is an action system, designed to scan the world and to track objects and events. Without the ability to control eye movements, to keep the fovea on a target, the visual system is functionally useless (von Hofsten, 2003). Like looking, a function of prehension is to bring a highly sensitive information-gathering device—the hands—to external objects. Prehension also functions to bring objects to the eyes for close-up visual inspection. Reciprocally, keeping the hands in view allows vision to aid in steering infants’ reaches and grasps.

Indeed, eye and arm movements may be sufficiently coordinated in newborns to jump-start visual-manual exploration and goal-directed reaching. For example, newborns will actively work to keep their hands in the field of view. While lying supine with small weights tied to both wrists, newborns allowed the weight to pull their arm down on the side toward the back of their heads but resisted the weight on the arm toward which their face was turned (van der Meer, van der Weel, & Lee, 1995). Their hand-to-face action did not merely reflect the fencing posture of the asymmetric tonic neck reflex because when view of the hands was occluded, both arms sank. When view of the hand toward the back of infants’ head was provided on a video monitor rather than directly, infants resisted the weight on the side opposite to the fencing posture (van der Meer, van der Weel, & Lee, 1995). Similarly, in a dim room, newborns kept their hand positioned in a narrow beam of light (van der Meer, 1997a). Viewing the hand appeared to be intentional and prospective because infants moved their hand when the light beam moved and they slowed down their arm movements before the hand arrived in the light, rather than after they noticed that they could see it.

Moreover, months before infants can reach or grasp, newborns orient toward objects with eyes and arms as if pointing their available “feelers” toward it (von Hofsten, 1982). When strapped securely around the chest into a slightly reclined seat or held by the head to prevent collapsing under the pull of gravity, newborns’ flailing arm movements became more directed toward a target object when the target was visually fixated than when they were looking elsewhere (Amiel-Tison & Grenier, 1986; von Hofsten, 1982).

**Common Paths to Prospectivity**

On a generous interpretation, infants’ earliest actions show the inklings of prospectivity. For example, by 1 month of age, infants can smoothly pursue a moving target with their eyes (Aslin, 1981; Rosander & von Hofsten, 2000; von Hofsten & Rosander, 1996), indicating an intent to follow the target and the ability to match target velocity with eye velocity. Smooth pursuit anticipates the target’s motion by extrapolating from the just seen motions to predict what will happen next (von Hofsten, 1997, 2003). However, neonates’ smooth pursuit occurs only in short bursts. As their eyes begin to trail behind the target, they are forced to use jerky, reactive, saccades to catch up (Phillips, Finoccio, Ong, & Fuchs, 1997). The initial saccade may so dramatically undershoot the target that a series of small steps may be required to move the eye to the goal (Aslin & Salapatek, 1975). Moreover, prospective control is fragile in neonates and easily disrupted by demanding tasks and unsupportive contexts (von Hofsten & Rosander, 1997). The target must be quite large and move slowly in predictable sinusoidal motions from side to side for neonates to keep it in sight (von Hofsten & Rosander, 1997). With larger objects infants perform fewer catch-up saccades because less precision is required to keep the target on the fovea (Rosander & von Hofsten, 2002).

As shown in Figure 4.5a, over the ensuing weeks, smooth pursuit comprises an increasing portion of infants’ visual tracking and corrective saccades comprise a decreasing portion, with the most rapid improvements between 6 and 14 weeks of age (Richards & Holley, 1999; Rosander & von Hofsten, 2002; von Hofsten & Rosander, 1997). Infants succeed at tracking smaller objects moving at faster speeds (Phillips et al., 1997;
Richards & Holley, 1999; Rosander & von Hofsten, 2002). By 4 to 5 months, looking is sufficiently predictive for infants to track targets moving behind an occluder (e.g., Rosander & von Hofsten, 2004). Brief exposure to an unoccluded trajectory makes infants’ looking more anticipatory to occluded trajectories so that their eyes wait on the far side of the occluder to catch the target when it reappears (S. P. Johnson, Amso, & Slemmer, 2003). By 3 months of age, infants can use rules instead of local extrapolation to predict the shifting location of a target (Adler & Haith, 2003; Wentworth, Haith, & Hood, 2002). By 5 months, they successfully track objects that abruptly reverse their direction of motion (von Hofsten & Rosander, 1997). By 6 months, they can use an arbitrary shape cue to anticipate the shifting location of a target (Gilmore & Johnson, 1995).

Infants’ prehensile actions show a similar developmental trajectory to looking. Reaching for stationary objects appears between 12 and 18 weeks (e.g., Berthier & Keen, in press; Clifton et al., 1993) and catching moving objects appears at approximately 18 weeks (von Hofsten, 1979, 1980). Just as infants’ first eye movements are saccadic and lagging rather than smooth and on-target, their first goal-directed reaches and catches are typically jerky and crooked. Initial reaches contain several “movement units,” where infants’ arms speed up and slow down and change directions before the hand finally contacts the toy (e.g., Berthier, Clifton, McCall, & Robin, 1999; Berthier & Keen, in press; Thelen et al., 1993; von Hofsten, 1980, 1983, 1991; von Hofsten & Lindhagen, 1979; Wentworth, Benson, & Haith, 2000). Corrections are more pronounced during faster reaches (Thelen, Corbetta, & Spencer, 1996).

Movement units and direction changes decrease after a few months until infants’ reaches and catches are made up of only two movement units, the first to bring the hand near the target and the second to grasp it (Figure 4.5b). Prospective extrapolations of target motion become increasingly resilient to loss of visual information. By 9 months, infants reach for moving objects on an unobstructed path but inhibit reaching when a barrier blocks the path (Keen, Carrico, Sylvia, & Berthier, 2003). By 11 months, infants catch moving objects as they appear from behind an occluder (van der Meer, van der Weel, & Lee, 1994).

What makes infants’ initial reaches so jerky and crooked? An initial suggestion was that movement units reflect visual corrections for a misaligned arm path (e.g., Bushnell, 1985). However, infants successfully reach for objects in the dark within a week or two of reaching in the light (Clifton et al., 1993), suggesting that they can use proprioceptive information to guide the reach. Indeed, by 5 to 7 months, infants can catch moving objects without sight of their hand by gauging the speed of the glowing object in the dark (Robin,
Berthier, & Clifton, 1996) and by 9 months, they preorient their hands to grasp in the dark (McCarty, Clifton, Ashmead, Lee, & Goubet, 2001). Several alternatives have been proposed. Possibly, the increased precision required to position the hand for grasping may prompt new reachers to plan the action as a series of small steps (Berthier, 1996, 1997; Berthier et al., 2005). Alternatively, some of the movement units might simply reflect unanticipated reactive forces (Berthier et al., 2005; Thelen et al., 1996; von Hofsten, 1997). Or, infants may have little motivation for efficient reaching (Witherington, 2005)—the functional penalty for extra movement units is low—and might even use variable arm paths to explore the capabilities of their new action system (Berthier, 1996, 1997; Berthier et al., 2005).

**Divergent Developments in Prospective Looking and Prehension**

Looking and prehension involve more than the eyes and the arms. Visual tracking requires fine-grained coordination between eye movements and head movements to keep the eyes on the target while the head and body move, especially during locomotion or while being carried (Daniel & Lee, 1990; von Hofsten, 2003). Prehension involves decisions about whether to use one or two arms, which arm to move, and coordinating reaching with grasping—all in relation to the features of the target object.

Prospective control over the components of looking and prehension develop asynchronously. Predictive eye movements do not transfer automatically to predictive head movements and predictive one-armed reaches do not transfer automatically to prospective control of grasping or decisions about whether to use one or two arms. For example, weeks after infants can smoothly track moving objects with their eyes, they begin to make large tracking movements with their heads (von Hofsten, 2004; von Hofsten & Rosander, 1997). However, infants have difficulty suppressing the vestibular-ocular reaction and initially their heads lag so far behind the target that they must put their eyes ahead of the target to keep it in view. The functional consequence of discord between eyes and head is a decrease in tracking precision.

Similarly, the components of prehension develop asynchronously. For many weeks after infants can smoothly transport their hand to an object, they misalign their hand position vis-à-vis the object’s orientation (Wentworth et al., 2000; Witherington, 2005) and fail to adjust their hand opening to the object’s size (Fagard, 2000; von Hofsten & Rønnqvist, 1988). Infants reach with their feet a full month before they reach with their hands (Galloway & Thelen, 2004). At the same age when infants show skilled reaches when one object is presented at midline, they respond haphazardly with one- and two-armed reaches to variations in object size (Corbetta, Thelen, & Johnson 2000; Fagard, 2000). Although infants may cross the midline of their bodies for two-armed reaches to large objects (van Hof, van der Kamp, & Savelsbergh, 2002), they fail to reach across midline when two objects are presented simultaneously (McCarty & Keen, 2005).

Like the developmental dissociations between the components of looking and prehension, prospective tracking and reaching for moving objects behind occluders appear at different ages. In general, infants demonstrate prospective control of looking before reaching. Their heads and eyes are on the target object when it reappears from behind the occluder while their hands seem lost or lag behind (Jonsson & von Hofsten, 2003; Spek & von Hofsten, 2001; von Hofsten, Vishton, Spek, Feng, & Rosander, 1998). By 11 months of age, infants can also intercept the occluded object with their hands (van der Meer et al., 1994).

**Centrality of Posture**

Maintaining balance is not optional. Actions require a stable postural base. Moreover, simply maintaining balance is usually not an end in itself (Riley, Stoffregen, Grocki, & Turvey, 1999). Rather, infants and adults maintain various postures to set up the necessary conditions for looking around, handling objects, holding conversations, or going somewhere (Stoffregen, Smart, Bardy, & Pagulayan, 1999).

**Nested Actions**

One reason for discrepant developments in the various components of looking and prehension is that actions are nested within other actions. Visual tracking with the eyes is nested within visual tracking with the head. Grasping with the hands and fingers is nested within reaching with the arms. Both looking and prehension—like all other actions—are embedded, in turn, within the most basic action of all: posture (Bernstein, 1967; E. J. Gibson & Pick, 2000; Reed, 1982, 1989).

Accordingly, one reason that newborns could demonstrate the inklings of prospective looking and reaching is that researchers eliminated the need for infants to
maintain the stable postural base required for action: Experimenters strapped infants around the chest into reclined seats or cradle-boards, supported their heads with side cushions, or held infants’ heads in their hands. Without the supporting scaffolds provided by the experimenters, young infants would not have been able to turn their heads to track or extend their arms to reach (Spencer et al., 2000; von Hofsten, 2003). By 4 to 6 months of age, infants exploit the features of a normal high chair to create a stable base for reaching by using the back of the chair and the edge of the tray to help support their trunks (van der Fits, Otten, Klip, van Eykern, & Hadders-Algra, 1999). Even with the benefit of supports, posture exerts effects on reaching through gravity. At 3 to 4 months, infants reach more frequently while strapped sitting into a special seat than while lying supine, where the entire body is supported by the cot, because less muscle torque in the arms is required while strapped sitting into a special seat than while lying supine, where the entire body is supported by the cot, because less muscle torque in the arms is required

**Anticipatory Postural Adjustments**

Establishing a stable postural base for actions requires infants to control balance prospectively (von Hofsten, 1993, 1997, 2003, 2004). Moving one part of the body to look, reach, or locomote creates disequilibrium by displacing the location of the entire body’s center of gravity. Moreover, movements of the head or limbs create reactive forces on body parts far removed because all of the body is mechanically linked (Gahery & Massion, 1981). Lifting an arm requires forces to be directed forward and upward. As a consequence, destabilizing forces of equal magnitude act in the opposite direction on the trunk. To prevent movement-induced disequilibrium from reverberating through the body, infants must anticipate postural disruptions and deal with them prospectively. In anticipation of the arms moving upward, adults activate neck and trunk muscles to stabilize the torso prior to activating arm and shoulder muscles to lift the arm. Or, adults shift the center of gravity backward prior to its being displaced forward. Without such prospective corrections to posture, the entire action can be disrupted and induce loss of balance and a fall.

Before 15 to 18 months of age, infants in a sitting posture rarely show anticipatory muscle activations of the trunk and neck to prepare for a reach (van der Fits & Hadders-Algra, 1998; van der Fits et al., 1999; von Hofsten, 1993). Instead, infants tend to activate arm, neck, and trunk muscles simultaneously. However, infants show other evidence of prospective control of balance during reaching. While strapped loosely around the waist in an infant seat, some 5-month-olds increased their reaching space by leaning forward (Yonas & Hartman, 1993). Attempts to reach decreased with increasing object distance, but infants who leaned attempted reaches at farther distances than the infants who did not lean. When balance constraints were altered with small wrist weights, 6-month-olds were less likely to stretch forward to reach than when they were not weighted (Rochat, Goubet, & Senders, 1999). Between 8 and 10 months of age, infants leaned forward in anticipation of raising their arm to reach for distant objects, suggesting that they perceived the additional stretch provided by their trunks and used the leaning posture to set up the framework for action (McKenzie, Skouteris, Day, Hartman, & Yonas, 1993).

As in a sitting posture, consistent anticipatory muscle activations in a standing posture appear between 15 and 17 months of age (Witherington et al., 2002). Lifting an object or pulling a weight with the arms causes a forward displacement of the center of mass. Adults’ calf muscles anticipate the disruption by firing just prior to activation of the arm muscles. In a clever adaptation of the adult paradigm, infants were encouraged to pull open a small weighted drawer (Witherington et al., 2002). Anticipatory postural adjustments became more frequent, consistent, and finely timed between 10 and 17 months. After 3 months of walking experience, 80% of the trials involved anticipatory activation of the leg muscles.
Some researchers have argued for age-related, developmental stages in the acquisition of a stable postural base for action (Assaiante & Amblard, 1995), with increasing levels of control through sitting, standing, and walking stages. However, other researchers argue that the changes are likely to be related to expertise, regardless of the period of development (B. Bril, personal communication, December 15, 2004). Novice adults sitting on a unicycle or standing while wearing Rollerblades are in the same precarious position as novice infants trying to sit and reach or stay upright and walk.

Perceiving Affordances

Affordances are possibilities for action. As described below, infants must learn to discriminate actions that are possible from those that are not. In some cases, infants’ learning is impressively flexible and transfers to novel situations. But, in other cases, learning is surprisingly specific and fails to transfer beyond the particulars of the training context. Together, flexibility and specificity of learning provide important insights into what it is that infants learn in the development of adaptive motor action.

The Actor-Environment Fit

Affordances reflect the objective state of affairs regarding infants’ physical capabilities and the behaviorally relevant features of the environment (J. J. Gibson, 1979; Warren, 1984). Actions are possible or not, regardless of whether infants perceive, misperceive, or take advantage of the possibilities. Because affordances are relational, the facts of embodiment must be taken with reference to the properties of the environment and vice versa. For example, walking is possible only when infants have sufficient strength, postural control, and endurance relative to the length of the path, obstacles along the way, and the slant, rigidity, and texture of the ground surface.

In fact, bodily propensities and environmental properties are so intimately connected for supporting motor actions that changes in a single factor on either side of the affordance relationship alter the probability of successful performance. Researchers have experimentally manipulated possibilities for locomotion by loading infants with weights, extending their leg length with platform shoes, and dressing them in roller skates or rubber- and Teflon-soled shoes to alter their body dimensions and level of postural control. (An alternative approach is to treat naturally occurring changes in infants’ bodies and skills as predictors.) To alter possibilities for locomotion by manipulating environmental properties, researchers have varied the slant, friction, and rigidity of the ground surface, created gaps in the path, terminated the path in a cliff, blocked the path with overhead or underfoot barriers, varied the height of stair risers and pedestals, varied the width of bridges spanning a precipice, and varied the substance and extent of handrails used for manual support (for reviews, see Adolph, 1997, 2002, 2005; Adolph & Berger, 2005; Adolph et al., 1993b).

Following Warren, Mark, and colleagues’ (Mark & Vogele, 1987; Warren & Whang, 1987) elegant psychophysical approach to describing affordances in adults, researchers have used a psychophysical staircase procedure to describe the probability of successful motor performance in infants (e.g., Adolph, 1995, 1997, 2000; Adolph & Avolio, 2000; Corbetta, Thelen, & Johnson, 2000; Mondschein, Adolph, & Tamis-LeMonda, 2000; Schmuckler, 1996; Tamis-LeMonda & Adolph, 2005). The staircase procedure is a classic method in psychophysics for estimating a perceptual threshold using a minimal number of trials (Cornsweet, 1962). When estimating a perceptual threshold, researchers plot the function spanning the increments where the observer’s accuracy is 1.0 to those where the observer guesses at 0.50 chance levels. To describe an affordance, researchers estimate a “motor threshold” along a function spanning the increments where success rates are 1.0 to those where success rates drop to 0. (The success rate is the number of successful attempts to perform the target action divided by the sum of successful plus failed attempts. Trials where infants refuse to attempt the action do not enter the calculations.) Coarser estimates require approximately 15 to 20 well-placed trials per infant; more precise estimates require upward of 40 trials per infant.

Like many psychophysical functions, the curves that characterize the transition from possible to impossible actions are generally steep S-shaped functions with long extended tails. As a consequence, most actions are either possible or impossible for a wide range of situations and have a shifting probability of success under a narrow range of increments. To illustrate, for a typical 14-month-old on a sloping walkway covered in rubber, the probability of walking successfully may be close to 1.0 on slopes from 0° to 18°, close to 0 on slopes from 28° to 90°, and show a sharply decreasing function on slopes
from 18° to 28° that encompasses the motor threshold (Adolph, 1995; Adolph & Avolio, 2000); see dashed curve in Figure 4.6a. For the same infant on a walkway covered in slippery vinyl, the entire function shifts leftward along the x-axis; see solid curve in Figure 4.6a. The probability of walking successfully may be close to 1.0 on slopes from 0° to 6°, close to 0 on slopes from 16° to 90°, and show a sharply decreasing function on slopes from 6° to 16° (Adolph, Eppler, Joh, Shrout, & Lo, 2005; Lo, Avolio, Massop, & Adolph, 1999).

Typically, infants show a wide range in motor thresholds even when tested at the same age. For example, the range for 14-month-olds walking down carpeted slopes is 4° to 28° (Adolph, 1995; Adolph & Avolio, 2000). The size of infants’ motor thresholds reflects their level of locomotor skill, duration of locomotor experience, age, body dimensions, and the specifics of the task (e.g., Adolph, 2002; Kingsnorth & Schmuckler, 2000; van der Meer, 1997b). In contrast to older children and adults where body dimensions are frequently the critical determinant of affordances for locomotion (Konczak, Meeuwson, & Cress, 1992; van der Meer, 1997b; Warren, 1984; Warren & Whang, 1987), with infants, skill and experience are generally the strongest predictors because between-subject variability is due more to differences in infants’ strength and balance than to the geometry of their bodies.

Learning to Perceive Affordances

The critical question for understanding the adaptive control of action is whether affordances are perceived—whether infants can select appropriate actions to meet their goals by detecting affordances (or lack of them) prospectively (see Adolph et al., 1993b for a review; E. J. Gibson, 1982; E. J. Gibson & Pick, 2000; E. J. Gibson & Schmuckler, 1989). In essence, the perceptual problem is to determine whether a potential future action lies on one of the tails of the affordance function or along the inflection of the curve. Because the location of the affordance function along the x-axis varies with changes in local conditions (e.g., whether the slope is covered in carpet or slippery vinyl, whether the infant is carrying a load), to solve the perceptual problem, infants would need to continually update information about the current status of their own action systems relative to environmental conditions.

For human infants and other altricial animals, determining the current state of affairs is no easy feat. The problem of perceiving affordances is complicated by

![Figure 4.6](image-url)
rapid, large-scale developmental changes in infants’ bodies, skills, and environments. As described earlier in this chapter, infants’ bodies grow in sudden overnight spurts; reaching, sitting, crawling, and walking skills improve most dramatically over the first few months after onset; and the environments to which infants are exposed are continually expanding. Moreover, in contrast to many other altricial animals, human infants spend prolonged periods—months—coping with objects and navigating surfaces after achieving each postural milestone in development. Typically, infants sit independently at approximately 6 months of age, crawl at 8 months, cruise (move sideways in an upright posture) at 10 months, and walk at 12 months (Frankenburg & Dodds, 1967). Given the changeable nature of the actor-environment fit, several authors have proposed that infants must learn to detect possibilities for action (e.g., Adolph, 2005; Campos et al., 2000; E. J. Gibson & Pick, 2000).

The classic paradigm for studying infants’ perception of affordances is the “visual cliff” (E. J. Gibson & Walk, 1960; Walk, 1966; Walk & Gibson, 1961). As illustrated in Figure 4.7a, crawling infants or other animals are placed on a narrow, 30-cm center board dividing a large glass-covered table. The glass is carefully lighted from beneath so that it is invisible from infants’ vantage point. On one side of the table, a patterned ground surface lies 0.6 cm beneath the glass. On the other side, the ground surface is 102 cm below the safety glass. Although locomotion is possible in either direction over the sturdy safety glass, visually, the “shallow” side specifies safe passage and the “deep” side specifies an impossibly large drop-off. With babies, caregivers beckon to their infants from first one side and then the other, with 1 or 2 trials per side. With other animals, the experimenters place them on the center board to descend to the shallow or deep side on their own.

Dozens of experiments have yielded fascinating but conflicting findings regarding the roles of locomotor experience and fear in infants’ avoidance of the apparent drop-off. The earliest studies showed that precocial animals such as chicks, kids, lambs, and piglets avoid the deep side of the visual cliff from their first days of life (E. J. Gibson & Walk, 1960; Walk & Gibson, 1961). If forcibly placed onto the safety glass, the animals brace their legs, bleat, tremble, and back up as if afraid of being unsupported in mid-air. Some altricial animals, such as kittens, rabbits, puppies, and monkeys, venture off the centerboard onto the deep side when they are newly locomotor or if they are prevented from acquiring visual feedback from their own locomotor activities by rearing them in the dark or in a “kitty carousel” (Held & Hein, 1963; Walk & Gibson, 1961). However, rats, also an altricial species, do not require visual experience with locomotion to avoid the drop-off (Walk, Gibson, & Tighe, 1957).

With human infants, a frequently cited cross-sectional study found that crawling experience predicted avoidance responses (Bertenthal & Campos, 1984; Bertenthal, Campos, & Barrett, 1984). At the very same age at testing—7.5 to 8.5 months of age—only 35% of inexperienced crawlers (M = 11 days of crawling experience) avoided the apparent drop-off compared with 65% of more experienced infants (M = 41 days of crawling experience). However, other cross-sectional experiments controlling for crawling experience or test age found opposite results, where experience predicted crossing onto the deep side rather than avoidance (Richards & Rader, 1981, 1983). Longitudinal data are inconclusive because infants learn from repeated testing that the safety glass provides support for locomotion (Titzer, 1995). Avoidance attenuated in some experienced crawlers, and other infants used a compromise strategy of detouring along the wooden wall at the edge of the table (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Eppler, Satterwhite, Wendt, & Bruce, 1997).

In some cases, locomotor experience appears to be posture-specific: The same crawlers who avoided the drop-off when tested on their hands and knees crossed over the cliff when tested moments later in an upright posture in a wheeled baby-walker (Rader, Bausano, & Richards, 1980). In other cases, locomotor experience appears to generalize across postures: 12-month-old walkers avoided the apparent drop-off after only 2 weeks of walking experience appended to their several weeks of crawling experience (Witherington, Campos, Anderson, Lejeune, & Seah, 2005).

Findings are equally discrepant with regard to the role of fear. Seven-month-olds showed accelerated heart rate—a measure associated with wariness or fear—when they were lowered toward the deep side of the visual cliff after only 1 week of crawling experience or 40 hours of upright locomotor experience wheeling around in a mechanical baby-walker (Bertenthal et al., 1984; Campos, Bertenthal, & Kermoian, 1992). However, crawling experience was not related to heart rate in 9- and 12-month-olds and the 9-month-olds showed cardiac deceleration—a measure associated with interest—to placement on the deep side (Richards & Rader, 1983).
Figure 4.7 Illustrations of several paradigms for testing infants’ perception of affordances for locomotion: (a) crawling infant approaching an apparent drop-off on a visual cliff. Source: From “A Comparative and Analytical Study of Visual Depth Perception,” by R. D. Walk and E. J. Gibson, 1961, Psychological Monographs, 75(15, Whole No. 519). Reprinted with permission; (b) crawling infant at the top of an adjustable slope. Source: From “Learning in the Development of Infant Locomotion,” by K. E. Adolph, 1997, Monographs of the Society for Research in Child Development, 62(3, Serial No. 251). Reprinted with permission; (c) sitting infant leaning forward over an adjustable gap in the surface of support; (d) crawling infant approaching an adjustable gap in the surface of support. Source: From “Specificity of Learning: Why Infants Fall over a Veritable Cliff,” by K. E. Adolph, 2000, Psychological Science, 11, pp. 290–295. Reprinted with permission; (e) walking infant exploring a bridge over a precipice; (f) walking infant using a handrail to augment balance on a narrow bridge. Source: From “Infants Use Handrails as Tools in a Locomotor Task,” by S. E. Berger and K. E. Adolph, 2003, Developmental Psychology, 39, pp. 594–605. Reprinted with permission. Caregivers (shown in a, not shown in b–f) stand at the far side of each apparatus and encourage infants to cross. Plexiglas ensures infants’ safety on the visual cliff. An experimenter (shown in b–f) ensures infants’ safety on the other obstacles.
Infants fussed slightly while lowered toward both the shallow and deep sides of the table but they also displayed positive vocalizations during placement on the deep side (Richards & Rader, 1983). Mothers’ fearful facial expressions produced higher rates of avoidance in 12-month-old crawlers on a 30-cm drop-off than did mothers’ joyful expressions, but the infants’ own facial expressions were positive or neutral—not negative or fearful—on the trials when they avoided the drop-off (Sorce, Emde, Campos, & Klinnert, 1985).

Albeit the most famous test paradigm, the visual cliff is not optimal. The discrepant findings may result from methodological problems stemming from the use of the safety glass, the procedure of starting infants on the center board, the fixed dimensions of the cliff, and the practice of testing each infant in only 1 or 2 trials. Due to the safety glass, visual and haptic information are in conflict. The drop-off looks risky but feels safe and is, in fact, perfectly safe as infants discover over repeated trials. Similarly, when the visual cliff was modified by replacing the drop-off with a deformable waterbed (agitated from below to create ripples), 14- to 15-month-old walkers refused to walk when they could feel the rippling surface, but walked over the waterbed when it was covered with safety glass (E. J. Gibson et al., 1987).

Moreover, placing infants on the narrow center board gives them little room to maneuver; sometimes avoidant infants accidentally move onto the deep side or start onto the glass and then retreat (Campos et al., 1978; E. J. Gibson & Walk, 1960). The fixed dimensions on the visual cliff preclude researchers from assessing whether perception is scaled to action and from testing the accuracy of infants’ perceptual judgments. The heights of the shallow and deep sides in the standard arrangement lie far on the tails of the affordance function, rather than along the inflection of the curve. Finally, data from a single trial per infant per condition are less stable than data from a single forced-choice trial (E. J. Gibson et al., 1987), and both procedures are more vulnerable to errant responses than methods that involve multiple trials per infant at each increment.

Specificity of Learning
Perception of affordances, like any perceptual judgment, involves observers’ sensitivity to the signal and observers’ response criterion. Both factors are highly influenced by the vicissitudes of single trials, especially with infant and animal subjects. To circumvent the methodological problems on the visual cliff, researchers have devised testing arrangements involving slopes, gaps, and barriers where perceptual information was concordant with the actual affordance, errors in judgment had actual consequences, mobile infants began on a runway several steps prior to the obstacle, and the dimensions of the test apparatus were adjustable. Most important, each infant contributed multiple trials at each stimulus increment (e.g., Adolph, 1995, 1997, 2000; Adolph & Avolio, 2000; Schmuckler, 1996; for examples with older children, see Plumert, 1995, 1997; Plumert, Kearney, & Cremer, 2004; Pufall & Dunbar, 1992; van der Meer, 1997b).

Following Warren, Mark, and others’ work with adults (e.g., Mark, 1987; Warren, 1984; Warren & Whang, 1987), researchers assessed the correspondence between infants’ perceptual judgments and the actual possibilities for action. Because infants are preverbal, perceptual judgments were determined based on an attempt rate: The number of successful plus failed attempts to perform the target action divided by the sum of successful attempts, failed attempts, and refusals to attempt the action. (The inverse avoidance rate yields the same information.) As shown in Figure 4.6b, decreasing attempt rates relative to the motor threshold provide evidence that perception is scaled to action. A close correspondence between attempt rates and the actual probability of success indicates that perceptual judgments are accurate.

Several experiments used the psychophysical procedure to examine infants’ perception of affordances for crawling and walking over slopes (for reviews, see Adolph, 2002, 2005; Adolph & Eppler, 2002). For each infant, researchers compared the correspondence between infants’ perceptual judgments and the actual probability of success. As illustrated in Figure 4.7b, flat starting and landing platforms flanked an adjustable slope (0° to 90°). Rather than safety glass, an experimenter followed alongside infants to ensure their safety. Infants received easy baseline trials after each failure or refusal to renew their motivation to crawl or walk; parents stood at the end of the landing platform, encouraging infants to descend and applauding their efforts after each trial. The procedure biased infants toward using a liberal response criterion (meaning a higher false alarm rate) and thus provided a conservative test of infants’ ability to detect affordances and respond adaptively.

Both cross-sectional (Figure 4.8a) and longitudinal data (Figure 4.8b) suggest that infants learn to perceive affordances for locomotion through everyday crawling
and walking experience. Moreover, learning appears to be specific to crawling and walking postures. In their first weeks of both crawling and walking, infants attempted slopes far beyond their ability and required rescue by the experimenter. Over weeks of crawling and walking, false alarms steadily decreased. Perceptual judgments gradually honed in to infants’ actual ability until attempts to descend closely matched the probability of success. The decrease in errors reflects remarkable behavioral flexibility because infants’ motor thresholds changed from week to week.

There was no evidence of transfer between crawling and walking postures. Infants tested repeatedly over weeks of crawling and walking showed no sign of savings in the transition from quadruped to upright postures, and infants in control groups matched for age and experience behaved similarly to infants tested repeatedly. Learning was so posture-specific that new walkers avoided descent of an impossibly steep 36° slope in their experienced crawling posture but plunged down the same hill moments later when tested in their inexperienced walking posture (Adolph, 1997). Twelve-month-old crawlers avoided a 50° slope; 12-month-old walkers stepped blithely over the brink (Adolph, Joh, Ishak, Lobo, Berger, 2005). As Campos and colleagues (2000) wrote, “The mapping between vision and posture that results from crawling experience will need to be remapped as the infant acquires new motor skills such as standing and walking. . . . In fact, remapping is likely to occur with the acquisition of every new motor skill in a continuously coevolving perception-action cycle” (p. 174).

Posture-specific learning is not limited to crawling and walking postures or to locomotion over slopes. In a modern twist on the classic visual cliff, Adolph (2000)
used the psychophysical procedure to test 9.5-month-old infants’ perception of affordances at the edge of a real 76-cm drop-off in sitting and crawling postures (Figure 4.7c to 4.7d). The apparatus was adjustable; the precipice lay below a 0- to 90-cm gap in the surface of support. The largest 90-cm gap was the size of the visual cliff. Caregivers encouraged their infants to lean forward over the gap to retrieve a toy. When tested in their experienced sitting posture (M = 104 days), infants perceived precisely how far forward they could lean without falling into the precipice; they matched the probability of attempting with the probability of success. However, when facing the gaps in their inexperienced crawling posture (M = 45 days), the same infants fell into impossibly large gaps. Nearly half of the sample in each of two experiments crawled over the brink of a 90-cm gap on multiple trials.

Similarly, infants showed specificity of learning between sitting and crawling postures when tested with barriers in their path. Over longitudinal observations, sitting infants reached around a barrier to retrieve a target object several weeks before they demonstrated the ability to crawl around the barrier (Lockman, 1984). When tested cross-sectionally, 10- and 12-month-olds were more successful at retrieving objects from behind a barrier when they were tested in a sitting position than when they had to execute the detour by crawling (Lockman & Adams, 2001). When the task was to learn a location based on repeated trips to mothers’ hiding place, experienced crawlers fared better than younger novice crawlers and better than older novice walkers (Clearfield, 2004). Younger crawlers attempted locomotion over a rippling waterbed on hands and knees but older walkers refused to step onto the waterbed or switched from their typical upright posture to quadruped (E. J. Gibson et al., 1987).

Infants may even show posture-specific learning between two upright postures: cruising and walking (Adolph, 2005; Adolph & Berger, 2005; Leo, Chiu, & Adolph, 2000). Like walking, cruising involves an upright posture. However, in contrast to walking, cruising infants move sideways and cling to a handrail or furniture for support. Using the psychophysical procedure, 11-month-old cruising infants were tested in two conditions. The handrail condition was relevant for maintaining balance with the arms in cruising: a solid floor with an adjustable gap (0 to 90 cm) in a handrail. The floor condition was relevant for maintaining balance with the legs in walking: a solid handrail with an adjustable gap (0 to 90 cm) in the floor. Infants correctly gauged how far they could stretch their arms to cruise over the gap in the handrail but the same infants erred when judging how far they could stretch their legs to cruise over the gap in the floor beneath their feet. New walkers erred in both conditions, failing to judge how far they could travel between manual supports in the handrail and stepping into impossibly large gaps in the floor.

**What Infants Learn**

What might infants learn that would lead to posture-specific perception of affordances? Several possibilities can be eliminated. In the slopes and gaps experiments where perceptual errors caused infants to fall, babies were not learning that the experimenter would catch them. Although the experimenter did rescue them as they fell, infants in longitudinal studies became more cautious over sessions, not more reckless; and in cross-sectional studies, the same infants who were caught dozens of times in their inexperienced posture avoided the obstacle when tested in their experienced posture.

Learning fear of heights is a frequently cited explanation (e.g., Campos et al., 2000). However, external manifestations of fear are not required for mediating an adaptive avoidance response, and it is unlikely that fear would wax and wane with changes in body postures. As on the visual cliff, crawling and walking infants in both cross-sectional and longitudinal studies showed primarily positive and neutral facial expressions and vocalizations, not fearful expressions or crying, as they avoided impossibly steep slopes (Adolph & Avolio, 1999; Fraisse, Couet, Bellanca, & Adolph, 2001; Stergiou, Adolph, Ali- bali, Avolio, & Cenedella, 1997). When infants’ mothers provided them with encouraging and discouraging social messages, 18-month-olds only deferred to their mothers’ unsolicited advice when the probability of success was uncertain (0.50 as determined by the psychophysical procedure). Moreover, they displayed primarily positive facial expressions and vocalizations at every increment regardless of whether they walked or avoided (Karasik et al., 2004; Tamis-LeMonda, Adolph, Lobo, Karasik, & Dimitropoulou, 2005).

Perhaps the most commonsense explanation is that infants learn that drop-offs, steep slopes, and the like are dangerous. However, the finding of posture-specific learning belies the notion that infants might learn to use particular facts about the environment to guide their actions, even when those facts hold true. Infants always require a sturdy floor to support their bodies. A 50° slope
and 90-cm gap are risky for every infant in every posture. The location of a hidden object is the same whether infants are sitting, crawling, or walking.

Similarly, the finding of flexibility within postures belies the notion that infants learn static facts about their physical propensities. In the longitudinal slopes study, experienced infants updated their perceptual judgments to reflect naturally occurring improvements in their crawling or walking skill (Adolph, 1997). In a cross-sectional experiment, when infants’ bodies were made more top-heavy and their balance more precarious by loading them with lead-weighted shoulder packs, infants recalibrated their perception of affordances from trial to trial (Adolph & Avolio, 2000). They correctly treated the same degree of slant as risky while wearing lead-weighted shoulder packs and as safe while wearing feather-weighted packs.

Along the same lines, infants do not learn simple stimulus-response (S-R) associations or fixed patterns of responding to particular environmental conditions. Rather, variety of responding is a common feature in studies where infants encounter obstacles to locomotion (e.g., Berger, 2004; Berger & Adolph, 2003). Experienced walkers displayed alternative locomotor strategies for coping with risky slopes: crawling down on hands and knees, sliding headfirst prone in a Superman position, backing down feet first, sliding in a sitting position, holding onto the experimenter for support, and avoiding traversal entirely by remaining on the starting platform (e.g., Adolph, 1995, 1997). Individual infants used multiple strategies at the same increment of slope within the same test session.

What, then, do infants learn that promotes flexible transfer across changes in bodies and skills but not across postural milestones? Since Thorndike’s (1906; Thorndike & Woodworth, 1901) classic theory of identical elements, researchers in motor skill acquisition have assumed that transfer depends on the extent to which elements of the training context are similar to elements of the performance context (Adams, 1987; J. R. Anderson & Singley, 1993). In our view, given the novelty and variability of motor actions, the notion of identical elements in simple association learning is far too static and narrow to account for learning to perceive affordances (Adolph & Eppler, 2002).

Harlow’s (1949, 1959; Harlow & Kuenne, 1949) notion of “learning sets” represented a try at something broader than simple association learning. His idea was that learners might acquire a set of exploratory procedures and strategies for figuring out solutions to novel problems within a circumscribed problem space (Stevenson, 1972). This set of information-gathering behaviors and heuristic strategies allows learners to solve novel problems of a certain type. The scope of transfer should be limited only to the boundary of the problem space. Rather than learning particular solutions, facts, or cue-consequence associations, learners are, in Harlow’s words, “learning to learn.”

In Harlow’s classic learning set paradigm, monkeys acquired a “win-stay/lose-shift” rule that would allow them to solve new instances of discrimination problems. But, solving novel problems in the circumscribed space of discrimination problems is a far cry from solving novel problems in the world of everyday motor actions. A fixed rule cannot provide the necessary flexibility to cope with a varying body, a varying environment, and moment-to-moment variations in biomechanical constraints.

Learning to learn in the context of controlling everyday motor actions requires something even bigger, something akin to the information-gathering procedures and strategies of Harlow’s learning sets, but more flexible than a rule. As suggested in the next section, infants assemble a repertoire of exploratory behaviors to generate the requisite perceptual information to specify affordances (Adolph & Eppler, 2002). Once infants can both generate and detect information about their physical capabilities and environmental properties, they are equipped to perceive possibilities for action. To the extent that each postural control system functions as a separate perception-action system (i.e., a distinct problem space), perceptual information will fail to transfer between postural milestones in development (Adolph, 2002, 2005).

The Perception-Action Loop

Perception and action are linked together in a continuously evolving loop (J. J. Gibson, 1979; von Hofsten, 2003). The textbook image of a motionless eyeball waiting to receive perceptual information is overly simplistic. In real life, eye, head, limb, and body movements bring the perceptual systems to the available information; “We don’t simply see, we look” (E. J. Gibson, 1988, p. 5). The traditional distinction between perception and motor control is largely artificial. Every movement is accompanied by perceptual feedback, and many types of visual, haptic, vestibular, and proprioceptive information do not exist without movement (J. J. Gibson, 1979). Reciprocally, prospective control of action relies on perceptual information. Perceptual feedback from
ongoing movements creates the potential for feedforward control. Thus, the perception-action loop can guide future actions rather than merely elicit them.

Over time, the loop comes to reflect developmental changes in infants’ perception-action systems, and experience refines infants’ actions toward more optimal function (E. J. Gibson, 1988; von Hofsten, 2003). Improvements in eye/head, manual, and postural control help infants glean visual information about external events and spurs their attention to the properties of objects and surfaces (Eppler, 1995; Needham, Barrett, & Peterman, 2002). Reciprocally, interesting visual displays motivate infants to seek information through looking. Feedback from interactions with objects and experiences with stance and locomotion facilitates improvements in prehension and locomotion.

For example, even the quiet touch of an infant’s hand resting on a stable surface provides information (and support) for postural stability. Infants in the early stages of upright balance used a manual support reactively to control their postural sway; they altered downward forces on the supporting handrail after their bodies began to sway (Barela, Jeka, & Clark, 1999; Metcalfe & Clark, 2000). More experienced walkers stabilized posture prospectively by changing the amount of downward force prior to body sway. Over the 4-month period between pulling themselves upright and acquiring 1.5 months of walking experience, the amount of vertical force applied to the handrail decreased by 50%.

**Sensitivity to Perceptual Information**

What is required to detect affordances? Perceptual information is a necessary but not a sufficient condition for perceiving possibilities for action. Without the appropriate information, infants have no basis for selecting or modifying actions and prospective control is doomed to fail: Walkers will trip over an obstacle in their path if they do not see it. Even with information available, infants must know where to direct their attention and be able to distinguish the relevant information structures. To illustrate with a classic (and hilarious) example of perceptual learning, both naive and expert adults looked at the same pairs of chick genitals, but only the experts could reliably differentiate their sex (Biederman & Shiffrar, 1987; E. J. Gibson, 1969). In short, prospective control will fail without both the appropriate exploratory behaviors to generate the crucial information and the perceptual expertise to tell the difference.

In the laboratory, experimenters can simply make information available to infants and measure their reactions. Differential responding would provide evidence for perceptual sensitivity. In the case of locomotion, insensitivity to visual information for depth, rigidity, slant, and self-motion is surely not responsible for perceptual errors at the edge of a cliff, waterbed, and steep slope. Infants show sensitivity to visual information about properties of surfaces and about the equilibrium of their own bodies long before they are independently mobile and even before they can sit up, reach, or fully control their heads. Newborns respond differentially to visual information for a drop-off versus solid ground, deformable versus rigid surfaces, and to surfaces slanting to different degrees in depth (e.g., Campos, Langer, & Krowitz, 1970; E. J. Gibson & Walker, 1984; Slater & Morison, 1985).

Prelocomotor infants also are sensitive to visual information for self-motion. Newborns pushed their heads backward in response to optic flow displayed on monitors along the sides of their heads (Jouen, 1988; Jouen, Lepecq, Gepenne, & Bertenthal, 2000). Remarkably, the speed and amplitude of their head movements were related to the velocity of the optic flow. Infants 3 to 4 months old distinguished a looming obstacle from an approaching aperture, indicating sensitivity to visual information about collision and safe passage (Gibson, 1982; Schmuckler & Li, 1998). Infants 3 to 6 months old even showed crude sensitivity to visual information for the direction of heading (> 22°) based solely on patterns of optic flow (Gilmore, Baker, & Grobman, 2004; Gilmore & Rettke, 2003).

The standard apparatus for testing sensitivity to visual information for self-motion is a “moving room” (e.g., Lee & Lishman, 1975; Lishman & Lee, 1973). Infants sit or stand on the stationary floor while the walls and ceiling in a mini-room around them swing forward and backward. Movement of the room in one direction simulates the optic flow that would result from a body sway in the opposite direction. Although the moving room puts visual and muscle-joint information into conflict (infants see that they are moving but feel that they are stationary), the sensation of induced sway is very compelling. To compensate for perceived disequilibrium, sitting infants sway their heads and torsos and standing or walking infants sway, step, stagger, and fall in the direction of the room movement (e.g., Bertenthal & Bai, 1989; Butterworth & Hicks, 1977; Lee & Aronson, 1974). Adults differentiate two kinds of flow structure, primarily using lamellar flow from movement of the side walls (optic texture elements stream in parallel along the sides of the path) to control their posture while
reserving radial flow from the front wall (optic texture elements stream outward from a central point of expansion) to guide their direction of heading (e.g., Stoffregen, 1985, 1986; Warren, Kay, & Yilmaz, 1996). Moreover, adults functionally differentiate the velocity of the flow, primarily using sway frequencies less than 0.5 Hz to control balance (Stoffregen, 1986; van Asten, Gielen, & van der Gon, 1988).

With age and experience, infants show more modulated behavioral responses to induced self-motion, increased functional differentiation of optic flow structures, and a tighter coupling between their sway responses and the timing and amplitude of room movements. In an upright position, younger children (<24 months) were literally bowled over in the moving room, but older children (2 to 6 years) and adults responded with smaller, more modulated postural sways (e.g., Schmuckler, 1997; Stoffregen, Schmuckler, & Gibson, 1989; Wann, Mon-Williams, & Rushton, 1998). Seated 9-month-olds showed functional differentiation of optic flow structure by producing directionally appropriate sways in response to whole room and side wall movement; 7-month-olds responded appropriately to whole room movement; but 5-month-olds responded indiscriminately (Bertenthal & Bai, 1989). Greater attention to the functional significance of optic flow structures in the older infants may have been facilitated by experience with locomotion; 8-month-olds with locomotor experience showed more postural responses to side wall movements than did precrawling infants of the same age (Campos et al., 2000; Higgins, Campos, & Kermoian, 1996). Similarly, standing and walking infants (12 to 24 months of age) displayed more staggers and falls to whole room and side wall movements than to front wall movements (Stoffregen et al., 1987). The dual task of steering while maintaining balance in a “moving hallway” caused more postural disruptions than walking along an open path (1- to 5-year-olds), and younger, less experienced walkers were more adversely affected (Schmuckler & Gibson, 1989).

Continuously oscillating movements of the whole room entrained sitting and standing infants’ postural responses so that they swayed back and forth like puppets in accordance with the room movements (Barela, Godoi, Freitas, & Polastra, 2000; Delorme, Frigon, & Lagace, 1989). The timing and amplitude of sway responses in older, more experienced sitters (9- and 13-month-olds) were more tightly linked to the frequency and amplitude of the continuously oscillating visual flow than the sways of younger, less experienced sitters (5- and 7-month-olds; Bertenthal, Rose, & Bai, 1997). Unlike adults, sitting 9-month-olds and standing 3- to 6-year-olds swayed in response to continuous room oscillations from 0.2 to 0.8 Hz (Bertenthal, Boker, & Xu, 2000; Schmuckler, 1997). However, like adults, sitting infants showed a linear decrease in the correlation between the swaying movements of their heads and the driving frequency of the room.

**Information-Generating Behaviors**

Outside the laboratory, disruptions to posture are generally self-induced by infants’ prior movements, not externally imposed by moving the surrounding room. There is no experimenter to distill perceptual information and present it to infants for their reactions. Instead, infants must do much of the information gathering for themselves. Even then, the availability of perceptual information does not guarantee that it will be detected.

To examine information gathering, researchers observe the exploratory behaviors of freely moving infants as they approach various obstacles in their path. Walking infants hesitated longer and engaged in more visual scanning and touching at the edge of a rippling waterbed (agitated from beneath) compared with the brink of a rigid surface (E. J. Gibson et al., 1987). Both crawling and walking infants—at all levels of age and experience—exhibited longer latencies and more looking and touching as they approached risky slopes compared with safe ones (Adolph, 1995, 1997; Adolph & Avolio, 2000; Adolph, Eppler, & Gibson, 1993a). Walkers generated visual and mechanical information by standing with their feet straddling the brink and rocking back and forth over their ankles. Crawl ers leaned forward with both hands on the slope and rocked over their wrists (drawn in Figure 4.7b).

Sitting, crawling, and cruising infants generated information about the size of a gap in the floor by stretching their arm (or leg in the case of cruisers) out over the precipice and then retracting it (Adolph, 2000; Leo et al., 2000). Figure 4.7c to 4.7d illustrates examples. Cruisers explored the size of a gap in the handrail by stretching and retracting their arms over the gap. Similarly, walkers explored possibilities for crossing a deep precipice via a narrow bridge by peering into the gap, dipping their foot into the gap, touching the bridge with their feet, and holding onto a support pole while stretching out a foot to see how far they could walk onto the bridge before having to let go (see Figure 4.7e; Berger &
Adolph, 2003; Berger, Adolph, & Lobo, 2005). Across studies, latency, looking, and touching were elevated on risky increments compared with safe ones.

On waterbeds, slopes, gaps, bridges, and the visual cliff, infants of all ages produced another kind of information-generating behavior: social expressions (e.g., Fraisse et al., 2001; Karasik et al., 2004; Richards & Rader, 1983; Sorce et al., 1985; Stergiou et al., 1997; Tamis-LeMonda & Adolph, 2005). Most infants vocalized (primarily babbles, open vowels, calls, and grunts rather than whimpers and cries; few words) and older infants also used manual gestures (e.g., arms outstretched toward their parents, pointing). Like perceptual exploration, infants’ social expressions were most frequent at risky increments. Researchers instructed caregivers about how to respond so as to manipulate or control for their social messages. However, under more natural conditions, presumably caregivers would respond with sensible and individually tailored social information in the form of encouragement or prohibition.

**The Real-Time Loop**

Largely absent from the infant and adult literatures on perceptually guided locomotion is a mechanistic account of the real-time, perception-action loop. What prompts infants in the ongoing course of locomotion to shift their attention to an obstacle, engage in concerted looking and touching, vocalize, look toward a caregiver, and so on? Given that infants’ exploratory behaviors are not random or indiscriminate, one thing must lead to another. The loop must spiral along from moment to moment until infants select a different action and begin again.

We offer two suggestions. First, not all information gathering need be deliberate (Adolph, 1997). Some types of information can arise serendipitously as a consequence of ongoing movements. Optic flow, for example, arises as a by-product of locomotion. With the eyes parked in front of the walker’s face, both radial flow for steering and lamellar flow for balance become instantly available (Patla, 1998). New walkers, however, have a problem. Tipping their heads downward to look at the ground near their feet throws their bodies off-balance (hence, toddlers’ “Frankenstein” gait). Thus, visual scanning of the near ground is likely to be deliberate.

In contrast, newly crawling infants tend to point their faces downward, perhaps because lifting the head requires more balance and neck strength. For them, visual information about the ground near their hands is cheaply available. Moreover, new crawlers frequently move in bursts punctuated by bouts of rocking. Such movements create torque around infants’ wrists and shoulders and shear force between their hands and the ground—all useful types of mechanical information (especially if they occur at the edge of a slope, waterbed, foam pit, or slippery surface) arising as a happy by-product of poor crawling skill.

Like looking and touching, social information gathering need not be deliberate. Individual animals (or entire species) can co-opt happenstance forms in adaptive ways. Young infants might vocalize without the intent to communicate and thereby serendipitously elicit useful social information from their caregivers. A similar notion of communicative exaptations is well documented in the animal literature. For example, rat pups emit ultrasonic vocalizations when they are separated from the nest. Although the squeaks serve a communicative function by prompting dams to return pups to the nest, pups are not deliberately calling to their mothers for help. The cause is simply a physiological response to rapid body cooling (Blumberg & Sokoloff, 2001, 2003). In the course of locomotion, rodents emit ultrasonic squeaks, horses wheeze, and dogs bark due to the compression of the thorax as their forelimbs hit the ground (Blumberg, 1992). Human infants 9 to 13 months old emitted grunts as a consequence of physical effort while crawling, moving from standing to squatting positions, and trying to lift the lid on a bottle (McCune, Vhiman, Roug-Hellichius, Delery, & Gogate, 1996). In the case of perceptually guided locomotion, infants’ vocalizations might arise as a by-product of arousal caused by the first sight of a large drop-off or steep slope; or, infants’ noises might stem from the physical exertion of mustering a crawling burst. Either way, an acoustic by-product of an underlying physiological maneuver does not preclude the listener from hearing a useful communicative signal. Regardless of infants’ initial intent, caregivers respond and are likely to precipitate a sort of “conversation” about the wisdom of attempting traversal.

A second suggestion for the precipitating events in a real-time perception-action loop concerns the role of visual information from a distance. Variations in the geometric layout of the terrain—cliffs, slopes, gaps, barriers, passageways, elevations, and so on—are specified by a host of visual depth cues. In addition to optical expansion and contraction, infants are sensitive to motion parallax, accretion and deletion of texture, stereoscopic information, convergence, and several pictorial depth cues (for review, see Kellman & Arterberry,
Thus, the real-time sequence of information gathering is likely to begin with visual information about the surface layout (Adolph, Eppler, Marin, Weise, & Clearfield, 2000). When the ground surface appears relatively flat and continuous (as in the baseline trials or control condition in most experiments), infants crawl or walk without hesitation or breaking stride. When infants detect depth information for a change in the layout, like adults, they may be prompted to modify their gait (Mohagheghi, Moraes, & Patla, 2004; Patla, 1991; Patla, Prentice, Robinson, & Neufeld, 1991) and to engage in more concerted looking and touching.

In most cases, reliance on visual depth cues is highly efficient. However, when the ground is deformable or slippery, visual information from a distance may fail to elicit the appropriate exploratory behaviors (Adolph, Eppler, et al., 2005; Joh & Adolph, in press; Lo et al., 1999; Marigold & Patla, 2002). Adults may rely on erroneous intuitions about the predictive relationship between deformable surfaces and rounded contours and between slippery surfaces and shine (Joh, Adolph, Campbell, & Eppler, in press). For example, more than 300 participants (15- to 39-month-old children and adults) walked straight into a large foam pit and fell. Apparently, the rounded edges and irregular surface of the foam blocks were not adequate to specify deformability. (Note, in the Gibson et al., 1987, waterbed experiments, event information for deformability was created by a researcher agitating the surface from underneath.)

Creating New Affordances for Action

Possibilities for action are not always constrained by infants’ immature bodies and limited skills. Happily, infants live in a world that is populated by caregivers who are willing to lend a helping hand, a world that abounds with objects and surfaces that can be incorporated as tools into an action plan. Although researchers typically do not consider social interaction and cognition to be central to the perception-action approach, social supports and tools can expand affordances for action and even create new possibilities for action.

Parents’ Role in Promoting Action

The development of action is not a lonely enterprise. Infants typically acquire new motor skills in a supportive social context (Tamis-LeMonda & Adolph, 2005). Before infants can exploit affordances for action on their own, caregivers create affordances for them. Caregivers scaffold prewalkers into walking infants simply by offering them a finger to hold onto for support. Similarly, in recent clever experimental manipulations, researchers have promoted new actions at earlier ages than if infants had to discover them on their own. For example, 3-month-olds who normally lack the motor skill to handle objects manually wore “sticky mittens” with Velcro-covered palms as they played with Velcro-edged toys (Needham et al., 2002). After the training, infants could pick up the toys and explore them as well as 5-month-olds who acquired their manual skills naturally. Seven-month-old prelocomotor infants learned to move around the room using a powered-mobility-device—a joystick controlled, battery operated buggy (D. I. Anderson et al., 2001; Campos et al., 2000).

Differences in child-rearing practices highlight parents’ role in providing opportunities for action. Parents promote action by organizing and constraining the circumstances surrounding infants’ developing skills (Reed & Bril, 1996). Caregivers decide whether infants are on the floor (Adolph, 2002; Campos et al., 2000), whether they have access to stairs (Berger, Theuring, & Adolph, 2005), and whether they sleep on their stomachs or on their backs (Davis, Moon, Sachs, & Ottolini, 1998; Dewey, Fleming, Golding, & Team, 1998). In some cultures, caregivers carry newborns as if they were a fragile carton of eggs and protect them from intense stimulation. In others, they throw newborns into the air and catch them, and stretch and massage their limbs (Bril & Sabatier, 1986; Hopkins & Westra, 1988, 1989, 1990; Super, 1976). Some cultures encourage new skills verbally. Others “train” infants, for example, by propping 3- to 4-month-olds in a special hole in the ground to promote sitting (Hopkins & Westra, 1988, 1989, 1990; Super, 1976) and jumping infants up and down to promote walking (Keller, 2003). As a consequence of the variation in child-rearing practices, infants acquire their sitting, crawling, walking, and stair-climbing at different rates—at later ages for children with fewer opportunities and less practice.

Tools Expand Possibilities for Action

Implementing a tool allows infants to create new affordances for action by themselves. When infants’ current physical abilities are inadequate for achieving a goal, tools can improve the actor-environment fit (Bongers, Smitsman, & Michaels, 2003). Tool use requires infants to (1) perceive a gap between their own motor abilities
and a desired goal, (2) realize that an object or environmental support can serve as an alternative means to bridge the gap, and (3) implement the tool successfully (Berger & Adolph, 2003). Although most researchers focus on the cognitive skills required by the second step (Chen & Siegler, 2000; Piaget, 1954), perceptual-motor skills are central to all three steps (Lockman, 2000). The first step to successful tool use involves perceiving (lack of) affordances for action—understanding that a desired object is too far out of reach or that the intended action is blocked by an obstacle (Berger et al., 2005). Developmentally, perceiving impediments to action appears before a concerted search for alternative means and both may appear prior to a search that incorporates an external object or environmental support (McCarty, Clifton, & Collard, 2001; Piaget, 1952; Willatts, 1984).

The means-ends problem solving that is so critical for the second step to tool use may have its roots in the perceptual-motor activity of relating objects to surfaces through actions (Lockman, 2000). For example, 8-month-olds relate objects to surfaces according to their respective material properties (Lockman, 2005). They perform banging actions with solid objects on solid tabletops but not when the object or surface is soft. Eventually, physical limitations cease to prevent infants from achieving their goals. By 10 months, infants show evidence of the second step to successful tool use. They extend their reaching abilities using sticks, hooks, rakes, and rings to drag over distant objects and show evidence of means/ends analysis by choosing an appropriate tool for a job (Bates, Carlson-Luden, & Bretherton, 1980; Brown, 1990; Chen & Siegler, 2000; Leeuwen, Smitsman, & Leeuwen, 1994). Similarly, in Köhler’s (1925) famous work on tool use in chimps, the animals pieced sticks together to retrieve an object beyond their reach.

The third step involves the biomechanics of tool use (Berger & Adolph, 2003; Berger et al., 2005). Beyond knowing that a tool is necessary for task completion and that certain items make appropriate tools, successful implementation of a tool requires knowing how to use it. Infants’ early action patterns may serve as the rudimentary foundations for later tool implementation (Lockman, 2000). Sliding objects back and forth over a surface may be an early precursor for writing and scribbling, and banging a hard object on a solid surface may prefigure hammering (Greer & Lockman, 1998).

Before 12 months of age, infants have difficulty planning an implementation strategy. Instead, they must correct their actions after they have already begun to use the tool. For example, 9- to 12-month-olds grab a spoon by the bowl-instead of the handle-end or hold it with the bowl-end pointing away from their mouth (McCarty, Clifton, & Collard, 1999, 2001). To correct, they must awkwardly rotate their hands or switch hands to get the bowl in their mouth. When experimenters highlighted the orientation of a spoon’s handle by repeatedly presenting it pointing in the same direction, 12-month-olds used the most effective radial grasp (McCarty & Keen, 2005). By 18 months of age, infants know which end of a spoon to grasp, how to grasp it, and how to plan the implementation so that they reach for the tool with the appropriate hand orientation instead of resorting to post hoc corrections (McCarty et al., 1999, 2001). Eighteen-month-olds can even adjust their typical tool-use strategies to cope with novel situations. Infants modified their grasp orientation, the location of their grip along the handle of the spoon, and the angle at which they held the spoon when they had to retrieve food through a narrow opening in a lid or when they had to use a spoon with a bent handle to scoop food from a bowl (Achard & von Hofsten, 2002; Steenbergen, van der Kamp, Smitsman, & Carson, 1997).

Tools are not limited to hand-held objects. Tool use can involve the whole body in action (Berger & Adolph, 2003). Köhler’s (1925) chimpanzees used poles to vault themselves into the air to retrieve bananas that were hanging from the ceiling. McGraw’s (1935) twins, Jimmy and Johnny, stacked boxes on top of each other to climb to a toy suspended high out of reach. Similarly, in a series of experiments involving whole-body tool use (Figure 4.7e to 4.7f), 16-month-old walking infants recognized that handrails could augment their balance for crossing narrow bridges (Berger & Adolph, 2003; Berger et al., 2005). When no handrail was available, infants refused to cross narrow bridges altogether. On wide bridges, infants ran straight across regardless of whether a handrail was available. Moreover, infants used wooden but not wobbly handrails for crossing narrow bridges, suggesting that they took the material composition of the handrail into account for determining its effectiveness as a tool (Berger et al., 2005).

**Summary: Getting into the Act**

Historically, developmental psychology has acquired a sort of split personality: Are we movement scientists, perception psychologists, cognitive psychologists, social psychologists, and language acquisition researchers? Or,
are we developmental psychologists? And if so, development of what? The fractionation of psychology into separate content domains has created a field of developmental psychologists who do not study common phenomena or even speak a common language. Research on motor development holds some promise for helping to forge a shared developmental science.

Perhaps the most far-ranging consequence of a perception-action approach to motor development is that motor skills have become relevant to developmental psychologists who would not normally worry about motor control. Rather than a simple response measure for making inferences about the workings of the mind, motor actions are now viewed as both a facilitator and beneficiary of psychological functions. On one side of the perception-action loop, researchers—like Piaget before them—study the effects of developing motor actions on perception, cognition, language, and social interaction (e.g., Biringen, Emde, Campos, & Applebaum, 1995; Campos et al., 2000; Needham et al., 2002; Sommerville & Woodward, 2005; Sommerville, Woodward, & Needham, in press). On the other side of the loop, researchers study the mental representations viewed as integral to motor actions (e.g., Gilmore & Johnson, 1995; S. P. Johnson et al., 2003, 2004; Munakata et al., 1997; Shinskey & Munakata, 2003; Spelke & von Hofsten, 2001; Spencer & Schöner, 2003). In short, researchers from a range of backgrounds are “getting into the act.”

In looking back over a career spanning 70 years, E. J. Gibson (1994) said in a keynote address to the American Psychological Society that nothing is so exciting as the search for encompassing principles. She offered ideas such as prospectivity and flexibility as a starting place for a grand unified theory of psychology, and she urged younger researchers to continue to search. In that spirit, we close with a final suggestion: The perception-action approach can serve as a model system for the study of developmental psychology. Research from the perception-action approach illustrates the utility and feasibility of studying infants, with all their many body parts and psychological functions, everything continually changing, embedded in a rich and varied physical environment populated by other people. Bridging the traditional divisions between content areas is certainly possible and may be the best bet for understanding how movements, learning, development—any kind of psychological change—occurs in the real-time processes of a moving and perceiving animal.

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