

Motor and Physical Development: Locomotion☆

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Glossary

Affordance A term drawn from Gibson’s perception-action theory referring to the fit between the physical properties of the environment and an animal’s physical abilities that makes a given action possible. Affordances exist regardless of whether they are detected or used.

Crawling Moving in a prone position, either with the belly on the floor or with the abdomen in the air. Infants may crawl using hands, arms, elbows, knees, feet, belly, and head for support and they may coordinate their limb movements into countless combinations.

Dynamic balance Keeping the body in equilibrium against gravity while the body is in motion (as in crawling or walking).

Newborn reflexes Movements produced by neonates in response to stimulation (e.g., stepping, grasping, sucking). Typically, these movements disappear after a few months. The movements are not truly reflexive because infants produce them spontaneously and they can be deliberately controlled and modified.

Posture Stationary and dynamic positions of the body that characterize a form of stance or locomotion (e.g., sitting, crawling, standing, cruising, walking). All postures except lying flat on the ground require balance control.

Prospective control Planning movements ahead of time based on perceptual information about upcoming obstacles and goals.

Walking A form of independent, upright locomotion. Infants achieve independent walking when they do not need to hold onto furniture or caregivers for support. In contrast to running, where both feet are off the ground for brief periods, in walking, at least one foot is always on the ground. In the swing phase, one foot is on the ground while the other foot swings forward. In the double support phase, both feet are on the ground.

Introduction: The Psychological Significance of Independent Mobility

Locomotion is a landmark developmental achievement. Independent mobility—whether by walking, crawling, cruising, or bum shuffling—offers new opportunities for learning about the environment, the self, and the relations between them (Gibson, 1988). Before they achieve mobility, infants are dependent on their caregivers to gain access to new vistas and places. Without transportation by their caregivers, infants’ view of the world is limited to the scenes revealed by turning the eyes and head. Exploration of objects and surfaces is restricted to things within arms’ reach. After they achieve mobility, infants are less dependent on their caregivers for making contact with the environment. They can change their vantage point to peer over the top of the coffee table or to explore beneath it. They can retrieve objects and transport them from place to place. They can choose to move away from their

caregivers or to follow after them. The onset of independent mobility marks a change in caregivers as well. Caregivers of mobile infants are more likely to express anger toward their infants, make demands of their infants, and prohibit infants' inappropriate actions (Biringen et al., 1995).

Locomotion requires infants to master dynamic balance control. Long before infants are independently mobile, they can produce the patterns of limb movements used for crawling, walking, and other forms of locomotion (Dominici et al., 2011; Piek and Carman, 1994; Thelen, 1979). But coordination is not enough. Mobility requires infants to produce coordinated limb movements while in a state of dynamic balance. In stationary postures such as sitting and standing, the body must be stabilized to allow the head and arms to move (Shumway-Cook and Woollacott, 2017). In contrast, during locomotion, the body must be destabilized in conjunction with movements of the arms and legs. To propel the body forward, infants must create the conditions of a fall and then recapture their balance on the fly from step to step (Bril and Breniere, 1993).

And dynamic balance is not all. Even a completely mindless mechanical device with no motor or controller (a toy slinky or a pair of jointed metal robot "legs"), can self-locomote down a uniform slope, showing impressive dynamic balance skills (Collins et al., 2001). But mobility in an infant cannot be completely mindless because locomotion does not take place in a uniform environment (Gibson and Schmuckler, 1989). The everyday environment is changeable with varied layouts, surfaces, and clutter in the path. Navigation through the everyday environment requires perceptual guidance to decide whether to modify ongoing movements (e.g., curb forward momentum to walk down a slope), select an alternative form of locomotion (e.g., slide down), or simply avoid going (e.g., if the slope is too treacherous). Locomotion must be generative and creative to come up with new ways of moving to suit the task at hand (Adolph and Robinson, 2013, 2015).

Compared with other motor actions, infants' success (and failure) at locomotion is easy to see. Movements of the eyes during visual tracking, the arms and hands during reaching and grasping, and the torso while keeping balance in stationary postures are typically so small and rapid that researchers require special motion recording equipment to see them (e.g., Kirkorian et al., 2012; Rachwani et al., 2015). In contrast, displacements of the whole body during locomotion are relatively large and slow and can be seen with the naked eye or on video (Adolph et al., 2012). Missteps and falls are obvious (as are their consequences when infants cry or incur injury). Given the psychological significance of locomotion and the accessibility of locomotor movements to observation, it is no wonder that parents commemorate infants' first steps in photos, videos, and "baby apps," and that researchers have been formally documenting the development of locomotion for more than a century.

Classical and Contemporary Approaches to Locomotor Development

Early Pioneers

By the early 1900s, amazing stop-action photography techniques were available for recording objects in motion such as horses galloping, birds flying, and human locomotion (Muybridge, 1957/1899). In the 1930s and 1940s, developmental psychologists co-opted and greatly expanded new recording technologies, and research on locomotor development entered its heyday. The early pioneers, Mary Shirley (1931), Myrtle McGraw (1935, 1945), and Arnold Gesell (1933, 1939, 1946), are best known for their detailed, normative descriptions of locomotor development and their emphasis on neuromuscular maturation as the agent of developmental change. Equally important, however, is their legacy of ingenious tasks and paradigms, their elegant and meticulous recording methods for capturing motor actions in real time, and their ambitious use of microgenetic methods (daily and weekly observations) to document changes over development.

With a diligence and persistence that set the modern standard, homely, everyday materials were combined with the finest film techniques of the day. Shirley (1931), for example, laboriously scored the x - y coordinates of footprints made from olive oil sprinkled with graphite to track the development of upright locomotion over the first 2 years of life. McGraw and Breeze (1941) traced infants' body position from still frames of high-speed film to observe locomotor development from birth until independent walking. Gesell (1928) built a "research hotel" in his laboratory so that he could observe infants continuously for several days (see also Thelen and Adolph, 1992).

What became of all this meticulous descriptive data? The writings of the early pioneers are full of quantitative data that chart changes in the frequency of various precursory and locomotor movements and detailed descriptions of improvements in the proficiency of crawling, walking, and a variety of other forms of locomotion (stair- and slope-climbing, descent from pedestals, swimming and diving, roller skating, and so on). Their descriptive and quantitative data have largely withstood the test of time. However, their prevailing adherence to a theory of neuromuscular maturation led the early pioneers to emphasize qualitative characterizations of stage-like changes in the development of locomotion and to ignore the immense intra- and interindividual variability that was apparent in the real-time performance and developmental appearance of each type of locomotor movement. They viewed the development of locomotion as an outward illustration of endogenous changes in the brain and body. In their view, locomotor behavior is an outgrowth of infants' maturing brains and bodies. Because motor behaviors are more accessible to observation than neuromuscular maturation, growth in locomotor development could provide insights into the corresponding growth of the nervous system.

Thus, variable developmental trajectories in the original datasets were depicted as invariant developmental sequences. McGraw (1945), for example, identified seven stages in the development of an erect posture. With tenacity unrivalled before or after his time, Gesell (1946) identified 23 ordered stages in the development of locomotion. The practice of cataloging motor achievements, identifying onset dates, and assigning stages to ages continues today with popular developmental screening inventories such as the

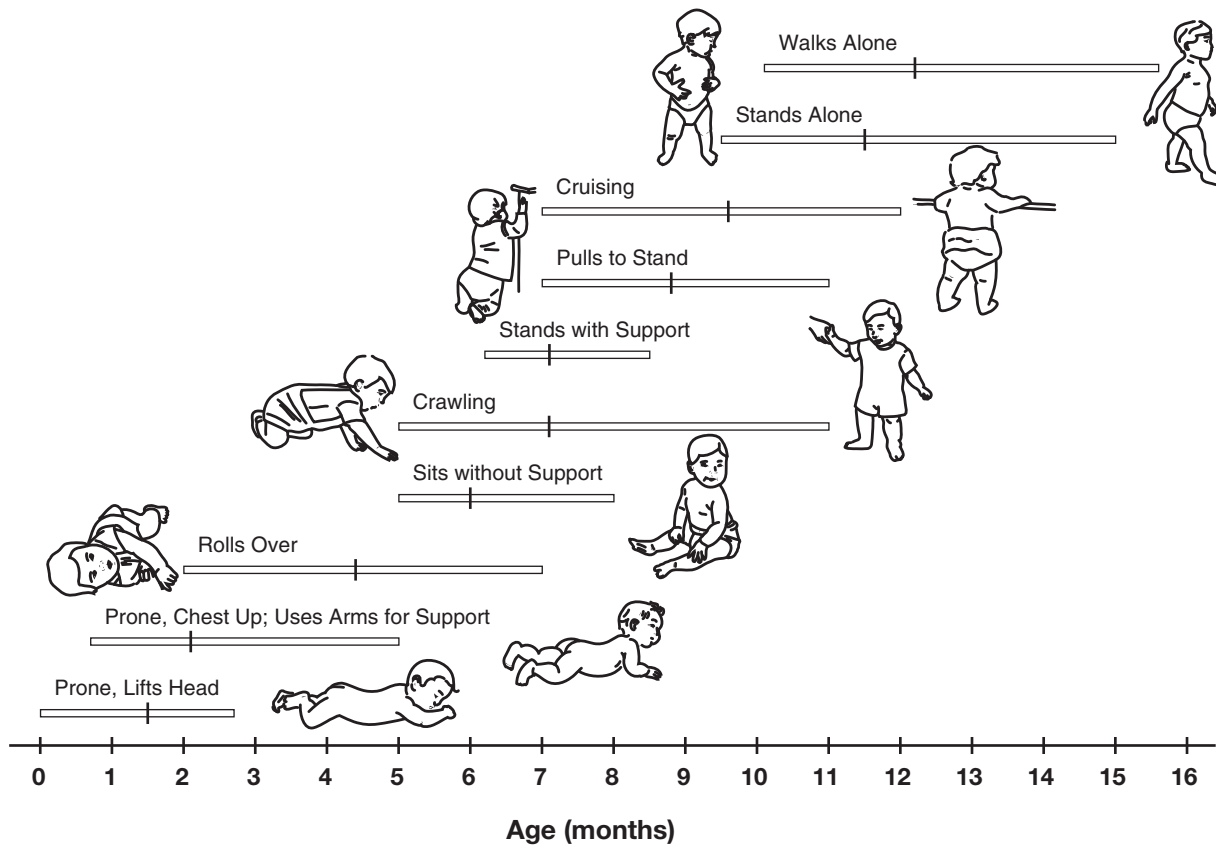


Figure 1 Infant motor milestone chart showing progression of postural and locomotor skills and age norms. Horizontal bars represent the normative range of skill onset; vertical lines show average age of first occurrence. As is typical in such depictions, skills are ordered by chronological age, implying a maturational sequence. Data from Bayley, N., 2006. *Bayley Scales of Infant and Toddler Development*, third ed. The Psychological Corporation, San Antonio; Frankenburg, W.K., Dodds, J.B., Archer, P., Shapiro, H., Bresnick, B., 1992. The Denver II: a major revision and restandardization of the Denver developmental screening test. *Pediatrics* 89, 91–97. From Adolph, K.E., Karasik, L.B., Tamis-LeMonda, C.S., 2010. Motor skills. In: Bornstein, M.H. (Eds.), *Handbook of Cultural Development Science. Domains of Development across Cultures*, vol. 1. Taylor and Francis, New York, pp. 61–88. Copyright © 2010, Taylor and Francis, reprinted with permission.

Bayley Scales (Bayley, 2006). Most developmental textbooks contain a chart that features infants' postural and locomotor milestones (Fig. 1). And based on data from infants in five countries (Ghana, India, Norway, Oman, and the USA), the World Health Organization proposed standards (what skills infants across the world *should* perform at what ages)—rather than norms (the skills infants from a particular population *do* perform at particular ages)—for the ages at which infants should achieve postural and locomotor milestones (Garza et al., 2006; Martorell et al., 2006).

Contemporary Approaches

Between 1950 and 1980, research on locomotor development was dormant. Possibly, the early pioneers had done their work too well. With reams of data recording infants' locomotor movements at various points in development and volumes of published works describing the ages and stages of locomotor development, there seemed little else for investigators to do. Beginning in the 1980s, contemporary researchers led by Eleanor Gibson, and Esther Thelen resurrected the study of locomotor development. New theories were proposed (perception-action and dynamic systems theories for Gibson and Thelen, respectively) and new motion recording technologies became available (sophisticated, high resolution devices such as force plates and high-speed motion capture systems and videotape, which allowed any researcher or parent to capture infants' movements). Once again, research took off (for reviews, see Adolph and Berger, 2006; Bertenthal and Clifton, 1998).

The received wisdom from the early pioneers depicted locomotor development as universal and decontextualized from the surrounds. But the starting assumption for most current work is that motor actions are “embodied” in the physical characteristics and constraints of infants' growing bodies and “embedded” in the features and constraints of the physical environment (Adolph and Robinson, 2015). The perception-action concept of “affordance” captures the functional significance of embodiment and embeddedness: Possibilities for locomotor action depend on the biomechanical facts of infants' bodies and the physical properties of the surrounding environment (Adolph and Kretch, 2015; Adolph and Robinson, 2015; Gibson and Schmuckler, 1989). Infants'

various body parts—their size, shape, mass, strength, coordination, and so on—affect the biomechanical constraints on locomotion. Reciprocally, possibilities for locomotion depend on the conditions of the environment in which infants' bodies are embedded: the effects of gravity acting on the body, the surfaces and media that support the body, and obstacles and impediments in the environment that constrain and shape forms of locomotion.

From a perception-action account, the development of locomotion cannot be divorced from function (Gibson, 1982; Gibson and Schmuckler, 1989). For locomotion to be adaptive, infants must select and modify actions to suit the constraints of the current situation. To make their way safely through the surrounds, infants must decide whether the ground is sufficiently flat, continuous, and clear of barriers to maintain balance and fit the body, and whether there is sufficient friction and rigidity to grip the surface and to support body weight. Moreover, actions should be planned prospectively before stepping over the brink of a cliff or losing balance on a slippery patch of ground. Given the relatively slow rate of neural conduction, reactive adjustments are only a strategy of last resort (von Hofsten, 2003, 2004). Thus, for infants to control locomotion adaptively, they must gather perceptual information about upcoming affordances in sufficient time to plan their next steps. For perception-action researchers, the study of locomotor learning and development is also the study of perceptual learning and development (Adolph and Berger, 2006).

The dynamic systems tenets of nested subsystems and emergent outcomes highlight the multiply determined nature of locomotor movements and the inter-related nature of the relevant components (Adolph and Franchak, 2016; Thelen and Smith, 1994). From a dynamic systems account, no component, including the brain, has logical priority for driving locomotor development (Thelen and Ulrich, 1991). New forms of movement emerge in development when all of the component subsystems are at a state of readiness. Locomotor movements are stable or variable depending on the levels of each component. The critical component at a given point in development or in a particular situation might be the status of the central nervous system, or it might be leg strength, balance control, the effects of gravity, the slope or friction of the ground surface, or some other peripheral factor.

The data that were so troubling for neuromuscular maturation theory—the fact that infants' locomotor movements are variable, idiosyncratic, and context dependent, and the finding that infants frequently straddle stages, skip stages, and backslide to earlier stages—are not problematic for contemporary theories. A guiding principle in current research is that unique moves can lead to common outcomes (Adolph, *in press*; Adolph and Franchak, 2016). The question is how. Dynamic systems researchers examine how multiple routes can converge on the same developmental pathway, and how similar routes can lead to different outcomes. Perception-action researchers study how individuals update their assessment of their own abilities from moment to moment and from one developmental milestone to the next.

A challenge for developmental researchers from both dynamic systems and perception-action frameworks is to identify the relevant aspects of infants' bodies and environments that create affordances for locomotion, even while these features are continually changing. The facts of embodiment vary due to developmental changes in body growth and abilities. Similarly, the features of the environment vary as infants' developing bodies and skills introduce them to new surfaces, places, and things.

Precursors of Locomotion: The Case of Newborn Stepping

Beginning with the early pioneers, researchers have located the developmental precursors to independent locomotion in infants' first, spontaneous limb movements. From the instant that their rudimentary muscles are innervated, fetuses exhibit limb and body movements. By 10 weeks of gestation, fetuses move their arms and legs singly, simultaneously, or in alternation, sometimes moving their limbs in conjunction with whole body activation as when they alternate their legs to turn a somersault (de Vries and Hopkins, 2005; de Vries et al., 1982; Luchinger et al., 2008). In the first weeks after birth, neonates continue to exhibit spontaneous limb and body movements (Piek and Carman, 1994; Thelen, 1979). As in the fetus, some of these movements resemble locomotor patterns such as swimming, crawling, and walking. Of course, fetuses and neonates are not maintaining balance or trying to locomote, but the propensity for coordinated, locomotor-like patterns is there.

Newborn stepping is the best-known example of precursory locomotor limb movements because it shows a fascinating U-shaped developmental trajectory (McGraw, 1932). Also known as the "stepping reflex," when newborns are held upright under their arms with their bare feet on a hard surface, they respond with alternating leg movements that look like exaggerated marching (Fig. 2A). Stepping movements typically disappear by the time infants are 8 weeks old and then reappear at around 8 months of age when infants begin to walk with caregivers holding their hands to provide balance and support.

From the traditional neural maturation account, first proposed by McGraw (1932, 1940) and adopted by many modern researchers, maturation of the central nervous system drives the disappearance and subsequent reappearance of stepping (Forssberg, 1985; Yang et al., 2004; Zelazo, 1983). Neonates' reflexive movements are subcortical (anencephalic infants step). Increasing myelination of the corticospinal tract suppresses the stepping reflex, and allows stepping to reappear under cortical control toward the end of the first year. Continued maturation of neural structures and circuitry increases information processing speed and efficiency so that infants walk independently at approximately 12 months of age.

Several lines of evidence argue against the traditional account. First, early stepping movements may not be reflexive. Fetuses and neonates exhibit stepping movements without the eliciting stimulus of the floor beneath their feet: They step with their legs dangling in the amniotic fluid or in the air (Barbu-Roth et al., 2014, 2015; Oppenheim, 1981); they step upside down in the uterus or with their feet on the ceiling (Peiper, 1963). Second, early leg movements can be cortically controlled: In operant conditioning experiments, infants kick a single leg, alternate their legs, or move their legs simultaneously when the appropriate leg movements are

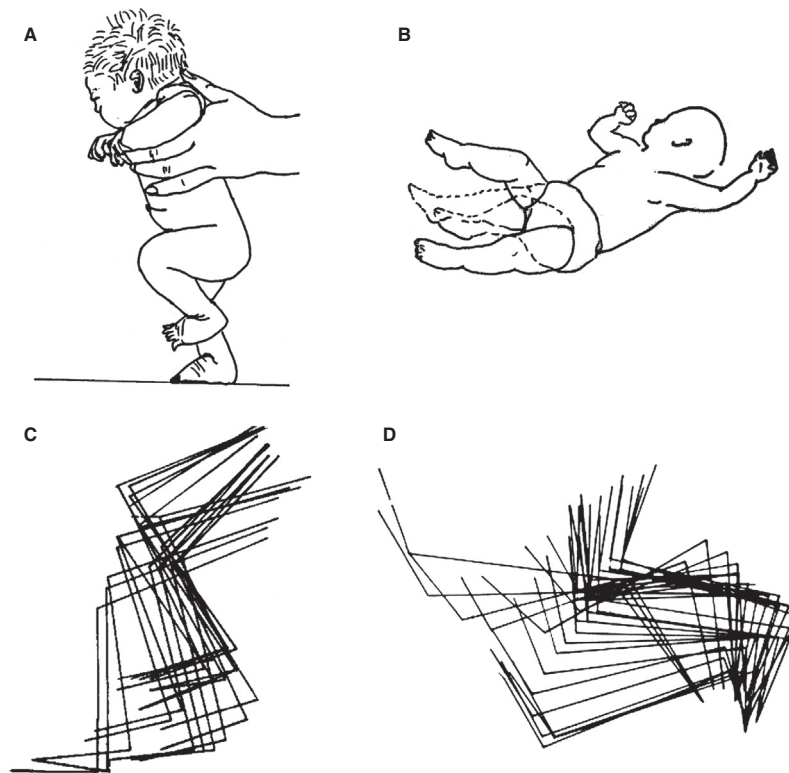


Figure 2 Alternating leg movements in newborn infants. (A) Upright stepping movements in neonates held with their feet against a solid surface. (B) Spontaneous kicking in infants while lying supine. (C) Stick diagrams of leg movements in upright stepping and (D) supine kicking in a representative 2-week-old infant. The lines chart the movements of one of the infant's legs at toe, ankle, knee, and hip every 33 ms. Figure reprinted from Adolph, K.E., Berger, S.E., 2006. Motor development. In: Damon, W., Lerner, R., (Eds.), *Handbook of Child Psychology*, vol. 2: Cognition, Perception, and Language, sixth ed. Wiley, New York, pp. 161–213. (A) Courtesy of Adolph, K.E., New York University. (B) From Thelen, E., 1979. Rhythmical stereotypies in normal human infants. *Anim. Behav.* 27, 699–715. Copyright © 1979, Elsevier, reprinted with permission. (C) and (D) From Thelen, E., Fisher, D., 1982. Newborn stepping: an explanation for a 'disappearing reflex'. *Dev. Psychol.* 18, 760–775. Copyright © 1982, the American Psychological Association, reprinted with permission.

linked with the jiggling of an overhead mobile (Angulo-Kinzler et al., 2002; Heathcock et al., 2005; Rovee-Collier et al., 1978; Thelen, 1994; Watanabe and Taga, 2006). Moreover, neonates increase upright stepping movements when exposed to optic flow that simulates movement through the environment (Barbu-Roth et al., 2009, 2014; Moerchen and Saeed, 2012). Third, Thelen et al. showed that alternating leg movements do not disappear; they are only masked when infants are held in an upright position (Thelen, 1986). Throughout the first year of life, infants kick their legs in an alternating pattern while lying supine (Fig. 2B). In fact, supine kicking movements have the same pattern of muscle activations and time-space trajectories as upright stepping movements. As shown in Fig. 2C and D, when leg movements are plotted as overlaying stick figures, supine kicking looks like upright stepping if the plots are turned 90° (Thelen and Fisher, 1982).

Thelen proposed that leg fat rather than the central nervous system is responsible for the U-shaped trajectory of upright stepping (Thelen and Fisher, 1982; Thelen et al., 1984). Normal gains in leg fat over the first few months of life typically outstrip gains in muscle strength. Alternating leg movements disappear in an upright position but not in a supine position because of the differential effects of gravity. While held upright with their feet on a solid surface, infants must partially support their body weight and work against gravity to flex their hip and knee. While lying supine, infants do not have the additional burden of supporting body weight, and gravity assists hip flexion by pulling the bent thigh toward the chest. Gravity, inertia, and the spring-like quality of the muscles and tendons help to extend the hip and spring the leg straight again. By 8 months of age, infants have sufficient muscle strength to lift their fat legs in an upright position.

In line with Thelen's body-based account, infants with thinner legs continue to display upright stepping movements at the same ages when infants with fatter legs stop stepping. Infants who normally take steps stop stepping when their legs are weighted to simulate the leg fat gained over the first 2 months of life. Infants who normally have stopped taking upright steps step once again when their legs are submerged in a tank of water that alleviates the effects of gravity (Thelen et al., 1984). Two-month-olds step with their legs dangling in the air, but not when required to partially support their body weight with their feet on a surface (Barbu-Roth et al., 2015). Finally, with a few minutes of daily exercise moving the legs in an upright position to strengthen their leg muscles, infants do not show the usual decline in stepping movements at 8 weeks (Zelazo et al., 1972).

Prerequisites for Locomotion: The Importance of Posture

Both classical and contemporary researchers view postural control as foundational for locomotion. The stage-like progressions in locomotion depicted by the early pioneers were really a series of distinct postural stages. Each subsequent posture marked the next triumph over gravity in an orderly march toward erect locomotion. As shown in Fig. 1, infants start with their head in the carpet and end by running across the floor. It is easy to see that upright walking requires postural control. But, as the early pioneers recognized, every form of locomotion requires postural control, including the forms that typically precede walking (cruising, crawling, bum shuffling, crabbing, pivoting, rolling, etc.) and the forms that follow it (running, skipping, sliding, stair climbing, walking backward, etc.). In any position except lying flat on the ground, postural control is required to fight the pull of gravity.

Terms like “static balance” and “stationary posture” refer only to the fact that the body is not changing location. Even while sitting or standing, the body is always slightly in motion, swaying gently within a cone-shaped region of permissible postural sway (Riccio, 1993; Riccio and Stoffregen, 1988). To keep balance in stationary and dynamic postures, infants must keep their bodies within the sway region. The size of the sway region depends on infants’ available muscle torque relative to the size of the gravitational and inertial forces pulling the body over.

Typically, infants achieve stationary postures before they achieve sufficient control over destabilizing forces to deliberately create the necessary disequilibrium to change locations without falling. They lift and turn their heads before they can roll. They prop on all fours before they can crawl on hands and knees. They stand upright before they walk. In the first few months after walk onset, infants’ strategies for deliberately inducing disequilibrium are variable and idiosyncratic. For example, they may stand up on tiptoe and allow themselves to fall forward, or wind their trunk like a spring and then use the angular momentum to bring their swinging leg around (McCollum et al., 1995; Snapp-Childs and Corbetta, 2009). Adult-like anticipatory control of gait initiation takes years to acquire (Breniere et al., 1989; Ledebt et al., 1998). Stopping at the end of a gait sequence is also problematic. Initially, infants collapse to the ground after crawling a step or two, and their walking sequences end when they crash into caregivers’ open arms. After several weeks of experience, infants can maintain a steady pace, modify their speed at will, and come to a controlled stop at the end of a sequence.

Crawling and Walking

Prone Progression

The typical precursors to crawling involve changes in body position and orientation without moving to a new location. Infants roll front to back and vice versa, transition from sitting to prone, pivot in circles on their stomachs, swim in place, and rock back and forth on hands and knees (Adolph et al., 1998; Gesell and Ames, 1940). Before they begin propelling themselves forward, some infants propel themselves backward by pushing with their arms, keeping their legs extended in a mermaid position.

Approximately half of the infants who eventually crawl display a period of “belly crawling,” in which the abdomen rests on the floor at some point during each crawling cycle (Fig. 3A). Some infants drag their abdomens along the floor like an army recruit going under barbed wire, and some inchworm along by repeatedly launching themselves from hands (or elbows) and knees (or toes) onto their bellies during each step (Gesell, 1946; Gesell and Ames, 1940). Other infants skip the belly crawling period of development. Their first success at forward prone progression is with their abdomens raised in the air during each crawling cycle, termed

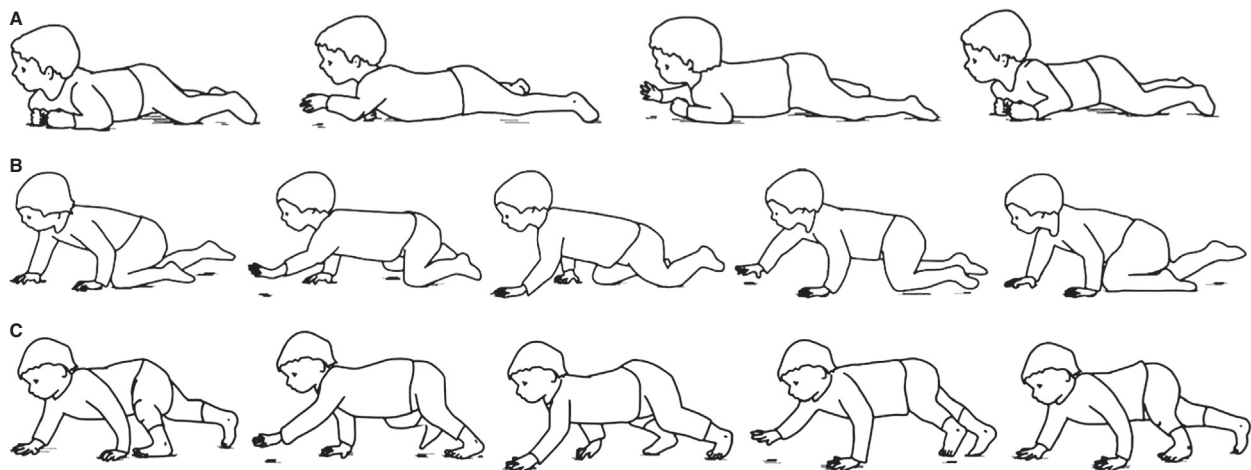


Figure 3 Some of the many individual variations in infants’ crawling patterns. Each sequence depicts one cycle from right to left: (A) “army” belly crawls, (B) “standard” hands-and-knees crawling, and (C) “bear” crawls on hands and feet. Modified from Patrick, S.K., Noah, A., Yang, J.F., 2012, Developmental constraints of quadrupedal coordination across crawling styles in human infants. *J. Neurophysiol.* 107, 3050–3061. Copyright © 2012, American Physiological Society, reprinted with permission.

hands-and-knees crawling (Fig. 3B). Former belly crawlers also display a period of hands-and-knees crawling and they do so at the same age, 8 months on average, as the infants who skip belly crawling (Adolph et al., 1998).

McGraw (1945) described prone progression as the most variable and idiosyncratic of all of infants' motor behaviors. Contemporary researchers would agree. Because belly crawling involves few balance constraints, infants show tremendous intra- and inter-individual variability in the body parts used for balance and propulsion and in the patterns of coordination between the limbs (Adolph et al., 1998; Freedland and Bertenthal, 1994; Patrick et al., 2012). From cycle to cycle, infants use their arms, legs, bellies, and heads in various combinations, sometimes pushing with only one arm or one leg and dragging the lame arm or leg behind, sometimes pushing with first the knee then the foot on one leg, sometimes resting on their belly and sometimes on their cheek, and so on. Interlimb timing is equally variable. Infants move arms and legs on opposite sides of the body together like a trot, same-side limbs together like a pace, lift front then back limbs into the air like a bunny hop, and so on. Belly crawlers simply power up their limbs and allow whatever idiosyncratic and arduous patterns they generate to emerge.

Even the prototypical hands-and-knees pattern is variable in terms of body parts used for balance and propulsion. Infants may crawl by balancing on a knee on one side and a foot on the other, balancing on two feet with the knees in the air like a bear, or using both the knees and feet in succession during each cycle (Fig. 3C). Variability in interlimb timing, however, shows a dramatic decrease in the developmental transition from belly crawling to hands-and-knees crawling (Adolph et al., 1998; Freedland and Bertenthal, 1994). Within 1 or 2 weeks after learning to keep their abdomens off the floor, infants converge on a diagonal, trot-like gait: The right arm moves and then the left knee, followed by the left arm and then the right knee (Fig. 3B). Presumably, the diagonal pattern provides the most stability while balancing on hands and knees.

Despite all the variability, and regardless of the body parts used for support and propulsion, infants' proficiency at crawling increases with each week of experience: Crawling steps become larger and faster. Infants who belly crawl show an advantage in proficiency compared with infants who skip belly crawling (Adolph et al., 1998). From their first week on hands and knees, former belly crawlers take larger, faster steps, and the belly-crawling advantage persists for several weeks. Moreover, the duration of infants' experience with any of the prone skills—even pivoting, rocking, and other skills that do not involve traveling somewhere—predict their proficiency at crawling on hands and knees (Adolph et al., 1998). Experience with precursory forms of prone progression provides infants with practice initiating disequilibrium and stabilizing their torso while moving their extremities. In summary, practice executing the variety of movements involved in belly crawling has beneficial effects on movements that use different parts of infants' bodies in different temporal patterns once they have sufficient strength to move on hands and knees.

Upright Locomotion

Walking upright is a unique accomplishment compared with other motor milestones. It is a developmental rite of passage marking the transition from infant to toddler, and like talking, walking is emblematic of human culture. However, achieving an upright posture can take infants several months. With increasing leg strength, infants pull to a stand gripping furniture, but fall back to their bottoms as their legs tire; when caregivers prop them against furniture, they bear weight momentarily with their legs hyperextended (Atun-Einy et al., 2012). Eventually, infants can stand with softly flexed knees while holding furniture or caregivers' hands for support. When infants acquire sufficient strength to hold part of their weight on one leg, they display "supported walking" (facing forward with caregivers holding onto both hands or supporting them under the arms) and "cruising" (moving sideways, using the arms for balance by holding onto furniture for support).

Most infants take their first independent walking steps around their first birthday, but the normal age range is extremely wide—from 10 to 16 months in Western cultures (see Fig. 1). Typically, infants' first walking steps are shaky and inconsistent (for reviews, see Adolph and Berger, 2006; Adolph and Robinson, 2013, 2015; Lacquaniti et al., 2012). Infants point their toes out to the sides, take tiny forward steps, and plant their feet so wide apart laterally that their step width may be larger than their step length (Fig. 4A). Velocity is slow, punctuated by relatively short periods with one leg in the air and relatively long periods with both feet on the ground. Movements at the hip, knee, and ankle joints are jerky and variable and muscle activity is



Figure 4 Example of walking footfalls from a pressure-sensitive gait carpet, revealing the shorter, wider, more variable steps of an infant walker with only 2 weeks of walking experience (A), and an infant with 2 months of walking experience (B). From Adolph, K.E., Robinson, S.R., 2013. The road to walking: What learning to walk tells us about development. In: Zelazo, P. (Ed.), *Oxford Handbook of Developmental Psychology*. Oxford University Press, New York, pp. 403–443. Copyright © 2013, Oxford University Press, reprinted with permission.

asynchronous. Infants' feet contact the ground flat-footed or toes first. Their knees and hips are flexed in the standing leg, causing the torso to lean forward; the hip is elevated as the leg swings forward, so the pelvis tilts from side to side (Hallemans et al., 2004). Infants' arms are flexed at the elbow in a frozen "high-guard" position. As in crawling, however, group averages mask tremendous intra- and interindividual variability. The typical developmental progression is only a rule of thumb. Some infants initially conquer dynamic balance by plunging forward and catching themselves before they fall; their first walking steps are long, their feet are pointed to the front, and one or both arms swing wildly (McGraw, 1945; Snapp-Childs and Corbetta, 2009). Regardless, the overall consequence is inefficiency.

The first 4 to 6 months of independent walking show the most rapid improvements in walking proficiency (Adolph et al., 2003; Bril and Breniere, 1993; McGraw, 1945). Rather than responding ad hoc to the outcome of their last step, infants' movements are uniform and consistent over the whole path of progression (Fig. 4B). Their toes point more forward, their steps are longer, and their feet are closer together laterally. Overall velocity increases; the proportion of the gait cycle with one leg in the air increases and the proportion with both feet on the ground decreases (Hallemans et al., 2006). Joint angles become smoother and more consistent, muscle contractions work in harmony, and infants' feet contact the floor with a heel-toe progression like adults. Energy expenditure is reduced as velocity increases and as the body is more extended and the pelvis stays level (Hallemans et al., 2004; Holt et al., 2006). Infants' hands are down at their sides and their arms swing reciprocally with the leg on the opposite side of the body. Although infants' average step length is short and average double support period is long relative to those of mature walkers, when moving fast enough, infants can take giant steps longer than their leg length and even display brief periods of running with both feet in the air (Badaly and Adolph, 2008). After the infancy period, walking patterns continue to improve, albeit more slowly, until 5 to 7 years of age, when children's walking becomes truly adult-like (Bril and Ledebt, 1998; Sutherland et al., 1988).

Both the early pioneers and contemporary researchers agree that the characteristic deficiencies and variability in infants' early walking patterns stem from the same problem that hinders walk onset: sufficient balance control to support the body on one leg while the other leg swings forward. To move the body forward, infants must generate propulsive forces to create disequilibrium. In fact, infants' initial walking deficiencies (slow walking, short wide steps, long double-support periods) are a solution for induced disequilibrium (Bonneuil and Bril, 2012; Bril et al., 2015). Infants are in such an exaggerated state of disequilibrium that they fall downward into each step; the vertical acceleration of their center of mass is negative when their foot contacts the floor (Bril and Breniere, 1993). In contrast, adult walkers propel upward at each step; the vertical acceleration of their center of mass is positive at foot contact. In essence, new walkers sacrifice balance to solve the problem of forward propulsion. They allow their bodies to fall forward while they stand on their stationary foot and then catch themselves mid-fall with their moving foot. Adult walkers control balance during forward propulsion by pushing upward with the foot supporting their body.

Starting with the early pioneers, researchers have debated the underlying factors that give rise to developmental improvements in walking. From a brain-based account, changes in neural structures and circuitry facilitate dynamic balance by increasing information-processing speed and efficiency and by expanding infants' ability to sequence their movements (Zelazo, 1998; Zelazo et al., 1989). From a body-based account, more slender body proportions and the lowering of infants' center of mass facilitate dynamic balance control by mitigating the size of destabilizing torque pulling the body over (Bertenthal and Clifton, 1998). Thus, infants require less strength to keep their bodies in balance. Moreover, an increased muscle to fat ratio provides infants with more strength to combat gravitational and inertial forces. From an experience-based account, practice moving in an upright position facilitates dynamic balance control by providing infants with opportunities to identify the critical parameters for keeping balance and their allowable settings (Adolph and Robinson, 2013). In addition, lifting the legs against gravity provides rigorous strength training in the leg muscles (Thelen, 1983).

Correlational and experimental evidence is consistent with all three explanations. In support of a neural maturation account, infants' brains increase from 30% to 70% of adults' brain weight over the first two years of life, and neural fibers become increasingly myelinated in the corticospinal tract (Johnson, 1998; Thatcher et al., 1996). Other psychological functions that require combinatorial sequences (e.g., language, symbolic play) appear at approximately the same age as walking (Walle and Campos, 2014). Infants' high-guard arm position co-occurs with a return to two-handed reaching, suggesting underlying brain linkages (Atun-Einy et al., 2014; Corbetta and Bojczyk, 2002). In support of a body-based account, chubbier infants tend to begin walking at later ages than slimmer, more maturely proportioned babies (Jaffe and Kosakov, 1982). Experimentally simulating fatter bodies or more babyish body proportions and decreased strength by dressing infants in lead-weighted body packs causes them to fall more frequently; when they manage to stay upright, infants wearing lead-loaded packs display less proficient walking patterns (Garciauirre et al., 2007; Vereijken et al., 2009). In support of an experience-based account, both controlled laboratory studies and natural cross-cultural experiments show that exercising infants' legs in an upright position facilitates walk onset (Adolph et al., 2010a; Adolph and Robinson, 2013, 2015; Zelazo et al., 1972).

To date, the three putative underlying factors have only been pitted against each other statistically. When experience (indexed by the number of days since walk onset), brain changes (indexed by infants' chronological age), and body proportions are compared statistically, experience independently predicts improvements in walking proficiency, accounting for statistical effects above and beyond those exerted by age and body proportions (Adolph et al., 2003). Neither age nor body proportions exert statistical effects above and beyond those produced by experience. However, these traditional indices of experience, brain, and body are too crude to provide satisfying explanations of development.

Although the state of the art in relating changes in the brain, body, and experience to locomotor development is still in its own infancy, new developments may inspire current research. For example, researchers have discovered that infants' skeletal growth is episodic. Height, for example, stays constant for several days or weeks. Then in the course of a single day, infants can grow nearly

2 cm (Lampl, 1993). New video-tracking measures of natural walking suggest that infants accumulate truly massive amounts of experience with balance and locomotion. Each hour, infants spontaneously take 2400 steps, travel the length of 8 football fields, and fall 17 times; over the course of a day, toddlers accumulate 14,000 steps, travel the length of 45 football fields, and fall 100 times (Adolph et al., 2012). Their paths meander wildly—infants turn, and they take forward, backward, and sideways steps. Infants constantly start and stop walking—about half of their walking bouts have only one to three steps (Cole et al., 2016; Lee et al., 2017). Advances in understanding the relations between brain changes and locomotor development may await a technology that can image brain activity while infants' bodies are in motion.

Historically, brain-based explanations are maturational accounts, experience-based explanations are learning accounts, and body-based explanations are agnostic regarding the respective roles of nature and nurture. Nonetheless, the historical compartmentalization of theories does not reflect researchers' sensitivity to the bidirectional nature of development. Both early pioneers and contemporary researchers agree that brain, body, and experience are likely to be inter-related. For example, maturation of the central nervous system and of infants' various body parts might spur infants to engage in more practice. Alternatively, practice might hone the neural circuitry and slenderize and strengthen infants' bodies.

Walking is the most recognized of infants' locomotor achievements, but it is not infants' final locomotor milestone. New walkers can carry objects in their arms and loads in tiny packs on the back, front, and sides of their bodies (Hsu et al., 2016; Karasik et al., 2012; Mangalindan et al., 2014; Vereijken et al., 2009). But infants' load carrying strategy differs dramatically from that of adults. Infants accommodate to the disruption in balance by leaning with the load and adapting their footfall patterns as best they can (Garciauirre et al., 2007). Older children and adults compensate for loads by leaning in the opposite direction of the added weight (e.g., leaning forward while carrying a heavy backpack). As a consequence, their footfall patterns are less disrupted.

Jumping and running are especially difficult because both feet must leave the ground simultaneously. Before infants can display a flight phase during running, they may "Groucho run," where they speed-walk with bent knees like the famous actor, Groucho Marx (Whitall and Getchell, 1995). Initial success at walking up stairs typically requires use of a handrail or caregiver's hand. Infants "mark time," meaning they bring both feet to one stair before lifting a leg to move to the next riser. A smooth, alternating gait for stair climbing can take years. Milestones for walking down stairs follow those for walking up (Berger et al., 2007). New patterns of interlimb timing (skipping, galloping, etc.), new ways to change body orientation (twirling, front and back somersaults, etc.), and incorporation of external devices into locomotion (tricycles, scooters, bicycles, etc.) appear during the preschool and grade school years.

Cultural Effects and Historical Changes

Motor development is "enculturated," meaning that caregivers' expectations, childrearing practices, and social interactions with infants affect the age of appearance and form of infants' postural and locomotor skills (Adolph et al., 2010a; Adolph and Robinson, 2015; see also Super and Harkness, 1986). The idea that infant locomotion is primarily the development of crawling and walking is an invention of 20th century Western culture (Karasik et al., 2010). Gesell and McGraw first transformed it into scientific fact, and contemporary researchers have perpetuated the idea. Although all healthy infants eventually walk, crawling is not universal. In some cultures, infants walk before they crawl or skip crawling altogether. Studies in the 1950s to 1980s reported that mothers in traditional communities in Africa and the Caribbean, for example, viewed walking as the outcome of training and exercise (Geber and Dean, 1957; Hopkins and Westra, 1988, 1989, 1990; Kilbride, 1980; Super, 1976). To encourage walking, mothers submitted their infants to vigorous daily exercise and massage (Fig. 5). Like the researchers who tested effects of upright stepping on later walking, mothers trained infants to support their own weight in an upright position and encouraged them to take upright steps. They stretched infants' limbs and rubbed their backs and heads. They threw newborns up in the air and caught them. They held infants by an arm or leg, and supported them at the torso rather than the head. The idea that infants must be handled like a carton of fragile eggs with the head always supported is also a Western invention.



Figure 5 Some groups of African and Caribbean mothers engage in elaborate daily handling routines to massage and stretch their infants' muscles and to encourage sitting and walking. These special exercises may contribute to the cultural differences in the ages at which motor milestones are achieved. Examples of formal massage and exercise practices used by caregivers in Africa, India, and the Caribbean to facilitate infants' motor development. Left to right: Passive stretching of infants' limbs; suspension and shaking by one arm, ankles, or head; encouragement to bear weight while standing upright, and taking steps with support. From Hopkins, B., Westra, T., 1988. Maternal handling and motor development: an intracultural study. *Genet. Soc. General Psychol. Monogr.* 114, 379–408. Copyright © 1988, the American Psychological Association, reprinted with permission.

In accordance with cultural differences in mothers' expectations and childrearing routines, infants reared in traditional communities typically began walking weeks earlier than infants in Western cultures. Similarly, mothers in some traditional African cultures exercised their infants' prone postures; accordingly, infants in those communities crawled sooner than infants who did not receive special training of prone skills (Super, 1976).

Even within a culture, historical changes in daily childrearing practices affect the form and schedule of locomotor development. For example, in 1900, 40% of middle-class infants in the United States skipped crawling (Trettien, 1900). Instead, they hitched along in a sitting position, crabbed on their backs, or logrolled. Hitching and so on may have been infants' solution to the long dresses that hampered their movements in a prone position. When infants tried to crawl, their knees caught at the edge of their long gowns pinning them in place.

More recently, researchers noted another link between historical changes in childrearing and infant crawling. For decades, Western pediatricians recommended that parents put infants to sleep on their stomachs to prevent aspiration of regurgitated milk. In 1994, the American Academy of Pediatrics launched a "Back to Sleep" campaign recommending that infants sleep on their backs to reduce the incidence of sudden infant death syndrome (SIDS). Back sleeping had the unintended consequence of delaying prone skills (Davis et al., 1998; Dewey et al., 1998). Compared with infants who sleep on their stomachs, back-sleepers sit, roll, and crawl at later ages; they display more hitching; and they score lower on measures of gross motor skill. To combat these unintended effects, pediatricians now advise parents to give infants "tummy time" while they are awake. More daily tummy time predicts earlier onset ages for sitting, rolling, and crawling, presumably because the prone position facilitates muscle strength in the arms and shoulders (Dudek-Shriber and Zelazy, 2007). Even something as seemingly mundane as a diaper exerts effects on motor development. Infants exhibit less mature walking patterns while wearing a cloth or disposable diaper compared with walking naked (Cole et al., 2012).

Locomotion in a Varied Environment

Functional locomotion involves movement over varied terrain. Infants' everyday environment rarely presents an open path over uniform ground. Instead, the path is cluttered with objects, furnishings, and people—obstructions underfoot and barriers impeding passage. The layout is varied with corners, doorways, small spaces, and open spaces. Changes in elevation create an up-and-down landscape—drop-offs, slopes, stairs, and so on. Ground surfaces can be high traction or slippery, rigid or deformable, bumpy or smooth.

The legacy of abstract stages from the early pioneers does not capture the – environmentally embedded nature of locomotor development. In contrast, perception-action theory focuses on body–environment relations in the development of locomotion. As exemplified in Figs. 6 and 7, a functional characterization of locomotor development must explain whether and how infants adapt their movements to variations in the surface layout (the arrangement of the environment in three dimensions) and to changes in the friction and rigidity of the supporting surface. From a functional account, navigation over irregular terrain involves a decision process—which movements to do and how to execute them—and consequently, locomotor development involves changes in the accuracy and efficiency of infants' locomotor decisions (Adolph and Robinson, 2013, 2015). Exploratory activity is critical for generating the requisite perceptual information to support infants' decisions.

Variations in Terrain

McGraw (1935) devised the first paradigms to test infants' responses to variations in the terrain—high pedestals and steep slopes. Infants blundered and fell on their first encounters with these apparatuses. Over weeks of experience, errors and clumsiness decreased, and were replaced with well-tuned, efficient performance, including modifications in infants' crawling and walking gaits on slopes and alternative strategies (backing feet first) for descending high pedestals. McGraw's descriptions are real page-turners because the experimenters allowed infants to experience the consequences of their mistakes and to fall.

A few decades later, Eleanor Gibson and Richard Walk (1960) created a safer paradigm dubbed the "visual cliff" to test infants' responses to variations in the terrain. The visual cliff is also among the most famous paradigms in developmental science, featured in introductory textbooks on development and perception (Adolph and Kretch, 2012). As shown in Fig. 6A, the apparatus is a large glass table, divided by a narrow starting board. On the "deep" side, a patterned surface on the floor far below the glass creates the visual illusion of a large drop-off. On the "shallow" side, the patterned surface is directly beneath the glass, providing visual information for a solid surface. When newly crawling infants are placed on the center starting board, they cross readily to their caregivers on both the deep and shallow sides. In contrast, infants with several weeks of experience crawling in their natural, everyday environment refuse to venture over the deep side (Campos et al., 2000; Campos et al., 1992).

Albeit famous and safe, the visual cliff is not an optimal test paradigm (Adolph and Berger, 2006; Adolph and Kretch, 2012). The safety glass presents infants with conflicting information: The deep side looks risky, but it feels safe (and it is). Infants quickly discover the illusion, precluding testing on repeated trials or in longitudinal observations. Moreover, the dimensions of the visual cliff are fixed so that researchers cannot test the accuracy of infants' responses or ask whether infants scale their locomotor decisions to the degree of the challenge.

Using a variety of new apparatuses and paradigms to circumvent the methodological problems with the visual cliff, contemporary researchers replicated the initial findings regarding the critical role of locomotor experience for adaptive responding at the edge

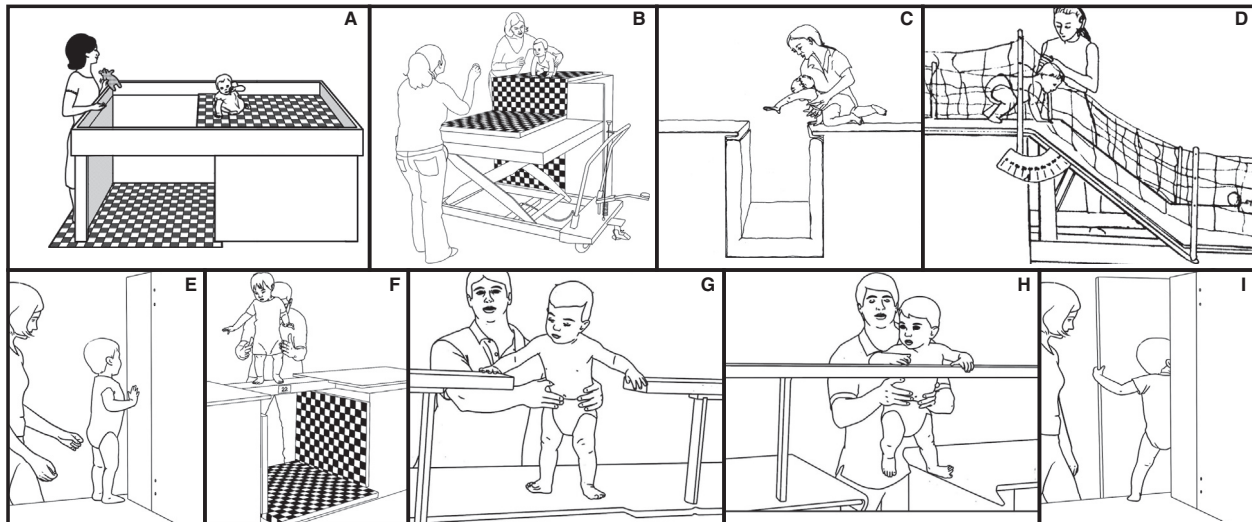


Figure 6 Illustrations of several paradigms for testing infants' locomotor decisions when challenged with variations in the surface layout. (A) Crawling infant approaching an apparent drop-off on a visual cliff. The surface on the deep side is 102 cm below the edge. (B) Crawling infant approaching an actual cliff with adjustable drop-off of 0–90 cm. (C) Infant approaching an adjustable gap (0–90 cm) in the surface of support in an unfamiliar crawling posture. (D) Crawling infant at the top of an adjustable slope (0° – 90°). (E) Infant negotiating a narrow ledge above a cliff. The ledge width adjusts from 0 to 70 cm. (F) Infant crossing a narrow bridge. The width of the bridge adjusts from 2 to 60 cm. (G) Cruising infant deciding whether to span an adjustable gap in the handrail (0–90 cm) used for support. (H) Cruising infant deciding whether to span an adjustable gap in the floor (0–90 cm). (I) Infant squeezing through an aperture (0–70 cm) between vertical walls. Figure partially adapted from Adolph, K.E., Berger, S.E., 2006. Motor development. In: Damon, W., Lerner, R. (Eds.), *Handbook of Child Psychology. Cognition, Perception, and Language*, vol. 2, sixth ed., Wiley, New York, pp. 161–213. (A) From Walk, R.W., Gibson, E.J., 1961. A comparative and analytical study of visual depth perception. *Psychol. Monogr. Gen. Appl.* 75 (15, Whole No. 519). Copyright © 1961, the American Psychological Association, adapted with permission. (C) From Adolph, K.E., 2000. Specificity of learning: Why infants fall over a veritable cliff. *Psychol. Sci.* 11, 290–295. Copyright © 2000, the American Psychological Society, reprinted by permission of SAGE Publications. (B) and (D) From Kretch, K.S., Adolph, K.E., 2013. Cliff or step? Posture-specific learning at the edge of a drop-off. *Child Dev.* 84, 226–240. Copyright © 2013, John Wiley and Sons, reprinted with permission. (F) From Kretch, K.S., Adolph, K.E., 2013. No bridge too high: Infants decide whether to cross based on the probability of falling not the severity of the potential fall. *Dev. Sci.* 16, 336–351. Copyright © 2013, John Wiley and Sons, reprinted with permission. (G) and (H) From Adolph, K.E., Joh, A.S., 2009. Multiple learning mechanisms in the development of action. In: Woodward, A., Needham, A. (Eds.), *Learning and the Infant Mind*. Oxford University Press, New York, pp. 172–207. Copyright © 2009, Oxford University Press, reprinted with permission. (E) and (I) From Franchak, J.M., Adolph, K.E., 2007. What infants know and what they do: perceiving possibilities for walking through openings. *Dev. Psychol.* 43, 1254–1261. Copyright © 2007, the American Psychological Association, reprinted with permission.

of a precipice. Wearing a harness to ensure their safety, newly crawling infants plunge over the edge of a real cliff (comparable in size to the visual cliff) or a water-filled abyss, whereas experienced crawlers refuse to go (Burnay and Cordovil, 2016). At the edge of a real adjustable drop-off (Fig. 6B), novice crawlers and walkers attempt to crawl or walk over the edge of 0- to 90-cm high drop-offs, treating trivially small “steps” and impossibly large cliffs equivalently (a nearby experimenter catches infants when they fall). In contrast, experienced crawlers and walkers precisely gear their decisions to the limits of their locomotor ability, attempting safe drop-offs within their ability, and refusing risky drop-offs beyond their ability (Karasik et al., 2016; Kretch and Adolph, 2013a). Similar results hold for adjustable gaps in the surface of support (0 to 90 cm wide), slopes (0° to 90°), ledges (0 to 75 cm wide), and bridges (0 to 60 cm wide) (Adolph, 1997, 2000; Franchak and Adolph, 2012; Kretch and Adolph, 2013b); see Fig. 6C–F.

A remarkable finding is that learning to perceive affordances does not transfer from an earlier developing posture to a later developing one (Adolph, 2008; Adolph and Robinson, 2015). What infants learn about body–environment relations over weeks of sitting does not appear to inform them when they begin crawling; what they learn over weeks of crawling does not help when they begin walking; and even experience cruising in an upright position does not ensure adaptive locomotor decisions when they begin walking. For example, experienced sitting infants precisely gauge their ability to lean over gaps in the surface of support. But the same infants fall repeatedly over the edge of impossibly large gaps when tested in a novice crawling posture (Adolph, 2000); see Fig. 6C. Newly crawling infants plunge headfirst over the brink of impossibly steep slopes (Fig. 6D). Their decisions become increasingly adaptive over weeks of crawling, until they gear their attempts to crawl to the actual affordance within a few degrees of accuracy. But when the same infants stand up a week later and begin to walk, learning starts all over again. As novice walkers, they blithely step over the brink of safe and risky slopes alike. And again, over weeks of walking, decisions become increasingly accurate and geared to the actual affordance for walking (Adolph, 1997; Adolph et al., 2008). Experienced cruising infants precisely gauge their ability to cruise across an adjustable gap (0–90 cm) in the handrail used for support (Fig. 6G). But while holding a continuous handrail, the same infants step straight into an adjustable gap (0–90 cm) in the floor beneath their feet (Fig. 6H)

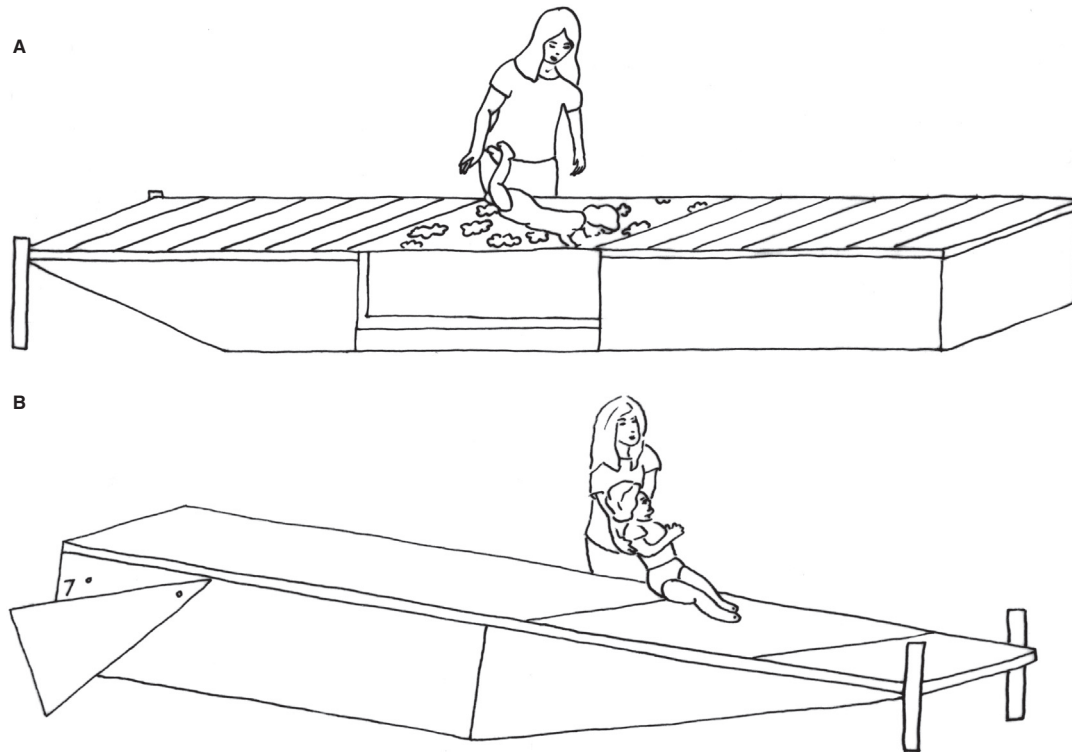


Figure 7 Illustrations of paradigms for testing infants' locomotor decisions when challenged with variations in rigidity and friction conditions. (A) Infant falling into deformable foam pit. (B) Infant slipping on a walkway interrupted by a low-friction Teflon floor. From Adolph, K.E., Joh, A.S., 2009. Multiple learning mechanisms in the development of action. In: Woodward, A., Needham, A. (Eds.), *Learning and the Infant Mind*. Oxford University Press, New York, pp. 172–207. Copyright © 2009, Oxford University Press, reprinted with permission.

as if they do not realize that upright locomotion requires a solid surface of support (Adolph et al., 2011). Newly walking infants do likewise.

Specificity of learning between sitting, crawling, cruising, and walking postures suggests that each postural milestone operates as a distinct perception-action system. Indeed, each posture involves very different control parameters, including different regions of permissible sway, key pivots about which the body rotates, muscle groups for balance and propulsion, vantage points for viewing the ground, correlations between visual and vestibular information, and so on. With each postural milestone, infants must identify the new parameters for the new balance control system and then learn to calibrate the settings of each parameter as they approach novel ground surfaces (Adolph, 2002, 2005, 2008).

The functional dissociation between postural milestones calls into question the widespread notion of functionally linked stages in a continuous march toward increasingly erect postures, first popularized by the early pioneers. Similarly, cultural differences and individual differences in the timing and appearance of various locomotor milestones belie the notion of obligatory stages in the development of locomotion. Although sitting, crawling, and cruising typically precede upright locomotion, apparently these precursory postures are functionally distinct postural control systems rather than obligatory prerequisites for walking.

A second notable finding is that everyday experience allows infants to update their assessment of affordances for locomotion from day to day and even from trial to trial. In longitudinal observations, experienced crawling and walking infants adjust their decisions about safe and risky slopes to take improvements in their locomotor skill into account (Adolph, 1997). A risky slope one week might be perfectly safe the next week when crawling skill improves. A safe slope for belly crawling might be impossibly risky for crawling on hands and knees. Experienced walking infants can even update their risk assessment after experimental manipulation of their body dimensions with lead-loaded shoulder packs or Teflon soled shoes that make balance more precarious (Adolph and Avolio, 2000; Adolph et al., 2010b). From trial to trial, they correctly treat the same degrees of slope as risky while wearing lead-loaded shoulder packs or Teflon-soled shoes but as safe while wearing featherweight shoulder packs or rubber-soled shoes. These results indicate that infants are not learning fixed facts about the environment (e.g., 24° slopes are risky) or fixed facts about their own bodies and skills (e.g., “I’m a poorly skilled walker” or “I’m a proficient walker”). Rather, infants are learning to detect the body–environment relations that hold for the current situation.

A third important finding is that infants appear to take the penalty for errors into account. When the penalty is falling into a precipice, experienced crawlers and walkers show highly adaptive decisions (as on drop-offs, slopes, and gaps). But when the penalty is entrapment, banging their head, or falling on flat ground or uphill slopes, they repeatedly err. Infants wedge themselves into impossibly narrow apertures (Fig. 6I), as do adults (Comalli et al., 2013; Franchak and Adolph, 2012)! Infants turn their bodies as they

approach the aperture, indicating that they perceive the tight fit, but they attempt to go nonetheless. Experienced crawling and walking infants attempt to crawl and walk up impossibly steep slopes; they fall repeatedly, but safely catch themselves (Adolph, 1995, 1997; Adolph et al., 1993). Experienced walking infants do not consistently adapt their posture to the height of overhead barriers and they do not consistently adapt their gait to step over impossibly high barriers underfoot (Herzberg et al., 2017; Schmuckler, 1996, 2013).

A final point: Experienced crawling, cruising, and walking infants discover and construct new forms of locomotion on the fly. When faced with a precipice too high for their typical mode of locomotion, infants test out various options and frequently display new behaviors not already in their repertoires. Crawlers slide down slopes flat on their bellies, head first, with arms outstretched like Superman (Adolph, 1997). They pivot in circles until realizing that they can back down a large drop-off feet first while facing away from their goal (Karasik et al., 2016; Kretch and Adolph, 2013a). Cruisers hunch over or cruise on their knees when only a low handrail is available for support (Berger et al., 2014). Walkers modify their gait to use a wobbly handrail for support while crossing narrow bridges (Berger et al., 2005). They stretch forward to use a solid handrail located arms' distance from a narrow bridge (Berger et al., 2010).

Variations in Friction and Rigidity

Variations in friction and rigidity present a different sort of problem for infants compared with variations in the surface layout (Adolph and Joh, 2009; Adolph et al., 2010; Joh et al., 2007). In contrast to slopes, gaps, cliffs, and the like, novel changes in friction and rigidity are not specified by reliable visual cues from a distance. Instead, friction and rigidity are resistive forces that emerge only when two surfaces come into contact, such as when the foot presses against the ground during walking. Because friction and rigidity result from the interaction between two surfaces, the appearance of a single surface cannot serve as a visual cue for friction and rigidity conditions. The same shiny floor, for example, may be slippery or resistive, depending on walkers' footwear and the velocity and angle of the foot as it touches the ground.

As a consequence, when approaching a novel patch of slippery or squishy ground, infants, like adults, are likely to step onto the offending surface and fall. Unlike adults, however, infants require multiple falls before they realize that a particular surface is too slippery or squishy to support locomotion (Joh and Adolph, 2006). For example, on their first encounter with an unexpectedly squishy surface, toddlers, preschoolers, and adults walk straight over a flat, rigid platform into a bumpy, deformable foam pit, and fall (Fig. 7A). Visual cues for the foam pit—the bumpy surface and rounded edges of the foam blocks and the coincident change in the color, pattern, and texture of the material covering the foam pit—are not sufficient to elicit hesitation or focused exploration on the first encounter with the obstacle. In fact, across ages, participants gasp when they fall, indicating that the consequences were unexpected. Although toddlers fall face-first into the foam pit, most require multiple trials before they avoid falling and some infants never show evidence of learning. Older children learn faster, and many, like adults, learn after only one trial.

Similarly, when toddlers approach an unexpectedly slippery surface—a large, white, shiny piece of Teflon—all fall on the first trial (Fig. 2B). Some infants require several repeated trials to show evidence of learning and the other infants fall over and over, never showing any evidence of learning (Adolph et al., 2010).

Infants' everyday experiences may explain why learning to link arbitrary visual cues (e.g., bumpy or shiny surfaces) with loss of balance is so difficult. Falling is commonplace in infants' everyday experience. A typical toddler falls 17 times an hour in the course of free play (Adolph et al., 2012). Most falls, however, are not elicited by a change in the ground surface. Infants do not slip, trip, or topple over because the ground is slippery or deformable. Although these challenges will induce falls, most frequently, infants slip and trip when they misplace their swinging foot on level, rigid, high-traction ground, or they topple over when they turn their heads or lift an arm. Everyday experience may lead to learned irrelevance (Adolph and Joh, 2009). That is, infants may learn to ignore the visual appearance of the ground surface because bumpy or shiny ground does not predict falling.

Feeling a questionable surface provides infants with the information they need for prospective control, but it does not allow them to extrapolate to future conditions. For example, if infants stop at the edge of a squishy foam pit, deformable waterbed, or slippery Teflon patch and feel the obstacle with their hands or feet, they are most likely to avoid traversal or to select an appropriate alternative method of locomotion for navigating it safely (Gibson et al., 1987; Joh and Adolph, 2006). Similarly, if they stop at the brink of a slippery slope and probe it with their hand or foot, they detect affordances (or lack of them) and respond adaptively. After touching the slope and feeling the lack of resistive forces, they recognize that walkable slopes are much shallower under slippery conditions than under high-friction conditions (Adolph et al., 2010).

However, the feeling of slip underfoot as infants approach a slippery slope is not sufficient to induce hesitation or exploration at the brink of the slope. Although a continuous surface covers the flat starting platform and slope, and despite the fact that infants must struggle to retain balance on the slippery starting platform, they walk straight down shallow slopes and fall. Adults also fail to extrapolate information from friction underfoot to an upcoming sloping surface. Despite feeling themselves slip on a flat platform adjoining the slope, they grossly overestimate their ability to walk down (Joh et al., 2007).

Exploration in the Service of Locomotion

Functional improvements in locomotor development are tied to developmental changes in infants' exploratory behaviors (Gibson, 1988). Head-mounted eye tracking shows that while crawling, infants' head points downward so they have easy visual access to the ground in front of their hands, but they cannot easily see the terrain several steps ahead (Kretch et al., 2014). While walking, infants'

head points forward, so they can easily see the surface layout and obstacles at a distance, but tipping their head down to see the ground near their feet can throw them off balance.

In real time, exploratory activity ramps up, from less to more costly forms of information gathering (Adolph and Eppler, 1998; Adolph et al., 2000; Kretch and Adolph, 2017). Head-mounted eye tracking shows that experienced walking infants see potential obstacles from a distance. If the going looks safe (e.g., a wide bridge or shallow slope), they just keep walking. But if they see something amiss (e.g., a narrow bridge or steep slope), they modify their gait during the approach. They slow down, stop at the edge, peer into the precipice, and probe the obstacle to obtain haptic and proprioceptive information. They poke a foot out onto the bridge, rub the slope with their feet, and generate torque at the relevant joints by making small stepping and swaying movements and rocking back and forth with their toes at the brink. If the obstacle feels safe, they attempt to walk down. But if it feels risky, they begin testing alternative locomotor strategies (e.g., sliding down slopes in sitting, backing, or prone positions). And if they fail to identify a viable alternative, they refuse to go.

Conclusions: Travel and the Mind

The development of locomotion is one of infants' greatest achievements. It is accomplished little by little as infants learn to cope with gravity, the constraints of their growing bodies, the expectations of their culture, and variations in the environment. Initially unique solutions in crawling and walking (and the myriad other forms that infants invent to move themselves from place to place) tend to converge on common patterns of interlimb coordination. But, common patterns of movements do not imply rigidity in the face of adversity. Infants take each encounter with everyday obstacles as an opportunity to employ a boundless repertoire of exploratory procedures, to discover new ways of modifying ongoing movements, and to construct alternative solutions when the current method of locomotion is impossible.

The development of locomotion reflects important changes across many domains of development—physical growth and biomechanics, as well as perceptual learning, cognition, and social interaction (Campos et al., 2000; Gibson, 1988). For infants, the ability to carry objects involves developmental changes in balance control (Hsu et al., 2016; Mangalindan et al., 2014). Carrying objects to interact with a caregiver reflects newly developing social skills (Adolph et al., 2010a; Karasik et al., 2011, 2014). Navigation through a cluttered environment involves perceptual exploration in the service of prospective control. Finding a new sliding position to descend a steep slope and using a handrail as a tool to augment balance are wonderful examples of means-ends problem solving.

Moreover, the development of locomotion facilitates change across many domains of development (Adolph and Robinson, 2015). The ability to go somewhere, to move and retrieve objects, and to leave caregivers behind creates new sources of information about the self in relation to places, surfaces, objects, and other people. Independent mobility has system-wide effects on psychological development. Indeed, as Joseph Campos et al. (2000) remind us, "travel broadens the mind."

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^{*}Change History: January 2018. KE Adolph, J Rachwani, and JE Hoch made changes throughout all sections and Figs. 1–6.

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