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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 with the body facing forward. 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 development of locomotion begins prenatally with spontaneous fetal movements. After birth, infants learn to cope with gravity and the continual flux of physical growth and variations in the terrain. Balance and strength are the critical factors for the emergence of new forms of locomotion and for improvements in proficiency. Experience is the critical factor for promoting adaptive responding to changes in body dimensions and variations in the environment. However, experience does not generalize from one postural milestone to the next. Independent mobility both requires and facilitates developments across multiple psychological domains.

The Psychological Significance of Independent Mobility

Locomotion is a landmark developmental achievement. Independent mobility offers new opportunities for learning about the environment, the self, and the relations between them. Before the onset of mobility, infants are dependent on their caregivers for gaining 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 the things within arms' reach. After the onset of 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.

Locomotion requires infants to master dynamic balance control. Long before the onset of mobility, infants can produce the patterns of limb movements used for crawling, walking, and other forms of locomotion. The really impressive achievement in the onset of mobility is the ability 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. In contrast, for dynamic balance 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.

The advent of mobility provides new possibilities for action. However, detecting possibilities for locomotion requires infants to perceive the surface layout and the friction and rigidity of each surface relative to their own physical abilities. 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. Selecting and modifying locomotor movements to suit the constraints of the current situation requires infants to generate and use new sources of perceptual information for controlling their motor actions adaptively.

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 observations require special motion recording equipment. In contrast, displacements of the whole body during locomotion are relatively large and slow and can be seen with the naked eye or on videotape. 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 'baby books' and home movies, 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. 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, Myrtle McGraw, and Arnold Gesell, 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 elegant and meticulous recording methods for capturing motor actions in real time, and their precedent of back-breaking microgenetic methods for documenting 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, 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 traced infants' body position from still frames of high-speed film to observe locomotor development from birth until independent walking. Gesell built a 'research hotel' in his laboratory so that he could observe infants continuously for several days.

What became of all this meticulous descriptive data? The writings of the early pioneers are full of quantitative data that chart improvements in the proficiency of crawling, walking, and other forms of locomotion and changes in the frequency of various precursory and locomotor movements. However, the prevailing adherence to a theory of neuromuscular maturation led the early pioneers to emphasize qualitative descriptions of stage-like changes in the development of locomotion and to ignore the immense intra- and intersubject variability that was apparent in the real-time performance and developmental appearance of each type of locomotor movement. The development of locomotion was viewed as an outward illustration of endogenous changes in the brain and body. In their view, locomotor behavior 'grows' as an accompaniment to 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, the variable developmental trajectories in the original datasets were depicted as invariant developmental sequences. McGraw, for example, identified seven stages in the assumption of an erect posture. With a tenacity unrivalled before or after his time, Gesell identified 23 ordered stages in the development of locomotion. Their quantitative data have withstood the test of time, and the practice of cataloging motor achievements, identifying onset dates, and assigning stages to ages continues today with popular developmental screening inventories such as the Bayley Scales. Most developmental textbooks contain a chart that features infants' postural milestones (Figure 1).

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), new motion recording technologies became available (including videotape which allowed any researcher or parent to capture infants' movements, and sophisticated, high resolution devices such as force plates and automatic motion capture systems), and once again research took off.

Whereas the early pioneers depicted locomotor development as universal and decontextualized from the surrounds, the starting assumption for most current work is that motor actions are embodied and embedded. The perception–action concept of 'affordances' captures the functional significance of embodiment and embeddedness: Possibilities for performing locomotor movements depend on the biomechanical facts of infants' bodies and the physical properties of the surrounding environment. 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. The size, shape, mass, strength, flexibility, and coordination of infants' various body parts 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 and the surfaces and media that support the body.

From a dynamic systems account, no component, including the brain, has logical priority for driving locomotor development. 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

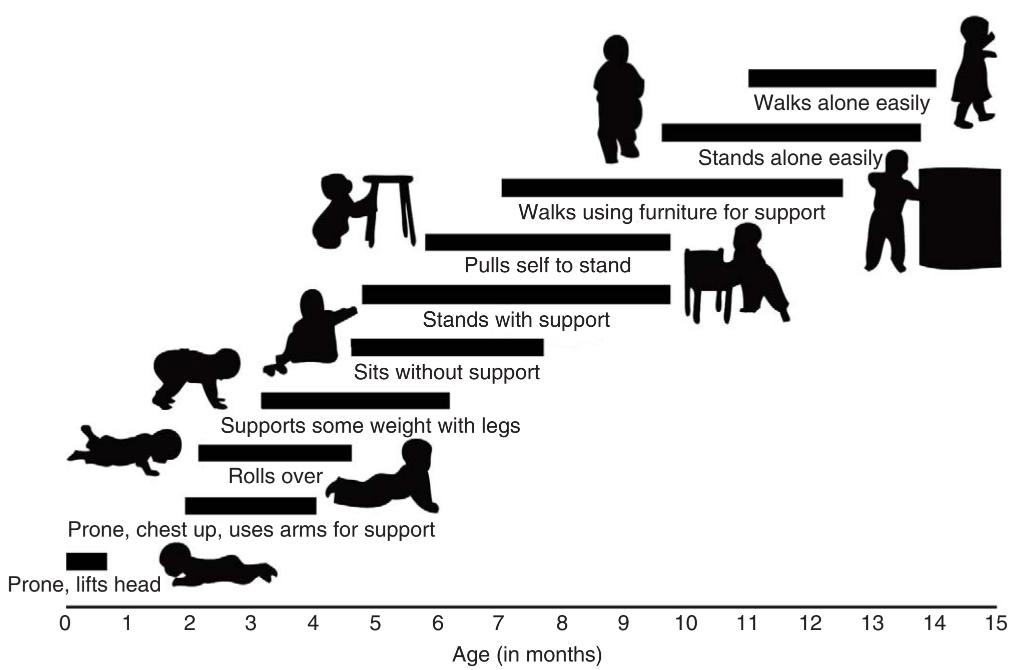


Figure 1 Infant motor milestone chart showing range of ages for achieving various postural and locomotor milestones. Source: from Siegler R, DeLoache J, and Eisenberg N (2003) *How Children Develop*, 1st edn. New York: Worth Publishers; Santrock J (2006) *Life-Span Development*, 10th edn. New York: McGraw-Hill; Frankenburg W, Fandal A, Sciarillo W, and Burgess D (1981) The newly abbreviated and revised Denver Developmental Screening Test. *Journal of Pediatrics* 99: 995–999, Copyright (1981), with permission from Elsevier.

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.

From a perception–action account, the development of locomotion cannot be divorced from function. For locomotion to be adaptive, infants must select and modify movements to suit the affordances of the current situation. Moreover, movements 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. 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.

The data that were so troubling for the 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. The question is how. Dynamic systems researchers examine how multiple routes can converge on the same developmental pathway. Perception–action researchers study how individuals update their assessment of their own abilities from step to step and from one developmental period 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 and places.

Precursors of Locomotion: The Case of Newborn Stepping

Since 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 enervated, 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. In the first weeks after birth, neonates continue to exhibit spontaneous limb and body movements. As in the fetus, some of these resemble locomotor patterns such as swimming, crawling, and walking. Of course, fetuses and neonates are not maintaining balance or trying to go someplace, 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. Also known as the 'stepping reflex', when newborns are held upright under their arms with their bare feet touching a hard surface, they respond with alternating leg movements that look like exaggerated marching (**Figure 2(a)**). 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.

From the traditional neural maturation account, first proposed by McGraw and adopted by many modern researchers, maturation of the central nervous system drives the disappearance and subsequent reappearance of stepping. Neonates' reflexive movements are subcortical

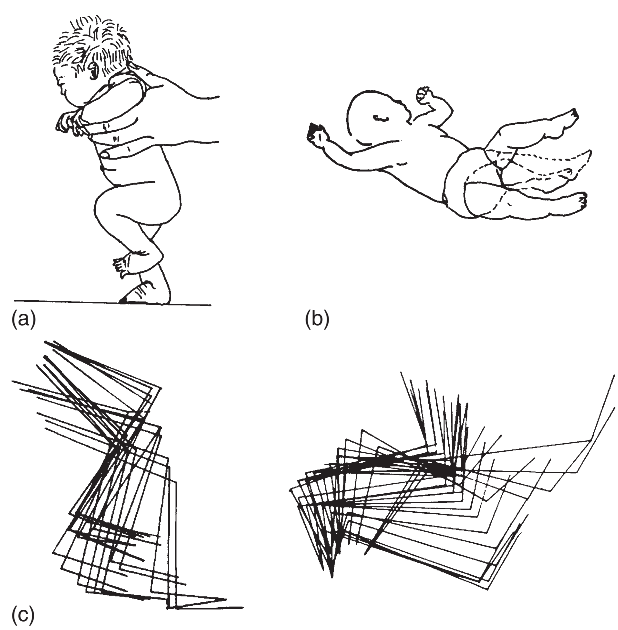


Figure 2 Alternating leg movements in newborn infants. Figure reprinted from Adolph KE and Berger SE (2006) Motor development. In: Damon W and Lerner R (eds.) *Handbook of Child Psychology: Vol. 2: Cognition, Perception, and Language*, 6th edn., pp. 161–213. New York: Wiley. (a) Upright stepping. Courtesy of Adolph KE, New York University. (b) Supine kicking. Reproduced from Thelen E (1979) Rhythmical stereotypies in normal human infants. *Animal Behavior* 27: 699–715, with permission from Elsevier. (c) Stick diagrams of leg movements in upright stepping and 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. Thelen E and Fisher D Newborn stepping: An explanation for a 'disappearing reflex'. *Developmental Psychology* 18: 760–775, 1982. Copyright © 1982, the American Psychological Association, reprinted with permission.

(anencephalic infants step). Increasing myelinization 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 an eliciting stimulus; they step with their legs dangling in the amniotic fluid or in the air, and they step upside down in the uterus or with their feet on the ceiling. Second, early leg movements can be cortically controlled; infants move a leg singly, alternate their legs, and move legs simultaneously when the appropriate leg movements are linked with the jiggling of an overhead mobile in operant conditioning experiments.

Third, Thelen and colleagues showed that alternating leg movements do not disappear; they are only masked when infants are held in an upright position. Throughout the first year of life, infants move their legs in an alternating pattern when they lie on their backs (**Figure 2(b)**). In fact, supine kicking movements have the same pattern of muscle activations and time-space trajectories as upright stepping movements. As shown in **Figure 2(c)**, when leg movements are plotted as overlaying stick figures, supine kicking looks like upright stepping if the plots are turned 90°.

Thelen proposed that leg fat rather than the central nervous system is responsible for the U-shaped trajectory of upright stepping. 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, infants must work against gravity to flex their legs at the hip. While lying supine, 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 to alleviate the effects of gravity. Finally, with a few minutes of daily exercise moving the legs in an upright position, infants do not show the usual decline in stepping movements at 8 weeks.

Prerequisites for Locomotion: The Importance of Posture

Both classical and contemporary researchers view postural control as the central prerequisite for locomotion. The stage-like progressions 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. 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, 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. To keep balance in stationary and dynamic postures, infants must keep their bodies within the region of permissible postural sway. 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 walking 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. Adult-like anticipatory control of gait initiation takes years to acquire. Stopping at the end of a gait sequence is also problematic. Initially, infants collapse to the ground after a crawling 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

McGraw described prone progression as the most variable and idiosyncratic of all of infants' motor behaviors. Contemporary researchers would agree. 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. Before they begin propelling themselves forward, some infants propel themselves backward by pushing with their arms, keeping their legs extended in the 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. Some infants drag their abdomens along the floor like a marine, and some repeatedly launch themselves from hands (or elbows) and knees (or toes) onto their bellies during each step. The other infants who eventually crawl 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 hands-and-knees crawling. Former belly crawlers also display a period of hands-and-knees crawling and they do so at the same age, on average (8 months), as the infants who skip belly crawling.

Because belly crawling involves less stringent balance constraints, infants show tremendous intra- and intersubject variability in the body parts used for balance and propulsion and in the patterns of coordination between the limbs. From cycle to cycle, infants use their arms, legs, bellies, and heads in various combinations, sometimes pushing with only one limb in a girdle 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 (**Figure 3**, rows for 'Army' and 'Inchworm' crawling). Interlimb timing is equally variable. Infants move arms and legs on alternate sides of the body together like a trot, ipsilateral 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 to emerge.

Even the prototypical hands-and-knees pattern is variable in terms of body parts used for balance and propulsion (**Figure 3**, rows for 'Standard' and 'Bear' crawling). 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. Variability in interlimb timing, however, shows a dramatic decrease in the developmental transition from belly crawling to hands-and-knees crawling. Within 1 or 2 weeks after learning to keep their abdomens off the floor, infants converge on a diagonal, near-trot gait: The right arm moves and then the left knee, followed by the left arm and then the right knee. 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. 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 skills that do not involve traveling somewhere – predict their proficiency at crawling on hands and knees. 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. Experience with precursory forms of prone progression provides infants with practice initiating disequilibrium and stabilizing their torso while moving their extremities.

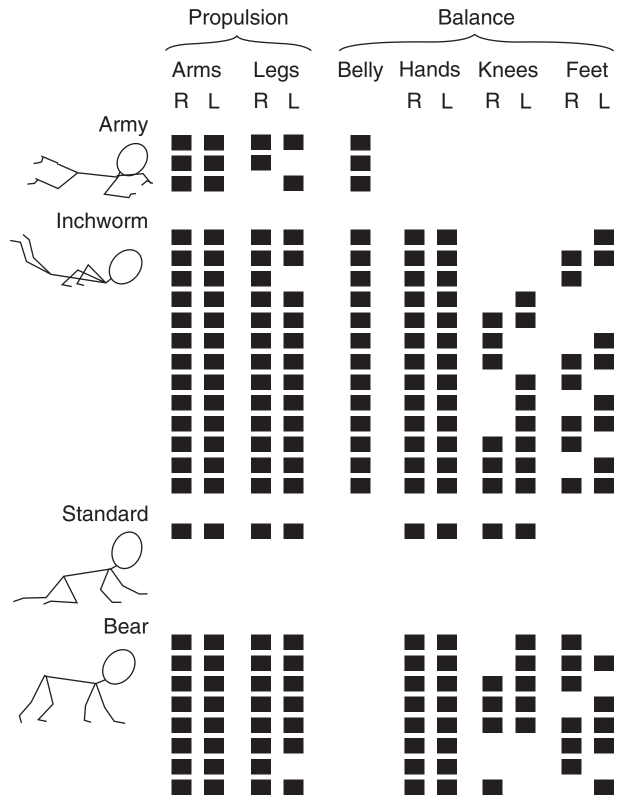


Figure 3 Some of the many individual variations in infants' crawling patterns. Left column illustrates four types of increasingly erect crawling postures: 'army' belly crawls, 'inchworm' belly crawls, 'standard' hands-and-knees crawling, and 'bear' crawls on hands and feet. Columns represent combinations of arms, legs, and belly used for propulsion and balance. Each row represents a unique crawling pattern displayed by at least one infant. Reproduced from Adolph KE, Vereijken B, and Denny MA (1998) Learning to crawl. *Child Development* 69: 1299–1312. Copyright (1998) by the Society for Research in Child Development, with permission from Blackwell Publishing.

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 infants' first words, 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. 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 9 to 17 months in Western cultures. Typically, infants' first walking steps are shaky and inconsistent. 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. 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. Infants' feet contact the ground on the toes or flat-footed. Their arms are flexed at the elbow in a frozen 'high-guard' position.

The first 4–6 months of independent walking show the most rapid improvements in walking proficiency (**Figure 4**). Rather than responding *ad hoc* to the outcome of their last step, infants' movements are uniform and consistent over the whole path of progression. 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. Joint angles become smoother and more consistent and infants' feet contact the floor with a heel–toe progression. Infants' hands are down at their sides and their arms swing reciprocally with the leg on the opposite side of the body. Walking patterns continue to improve, albeit more slowly, until 5–7 years of age, when children's walking becomes truly adult-like.

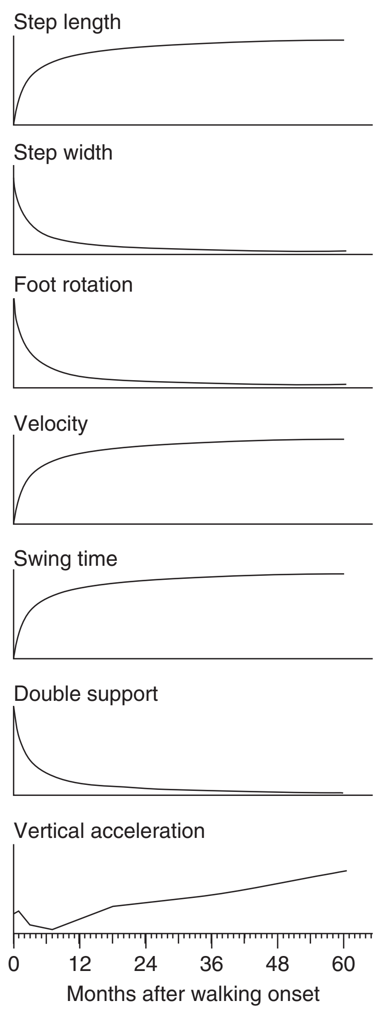


Figure 4 The characteristic time course of improvement in several measures of children's walking gait over the first 60 months of independent walking. Figure reprinted from Adolph KE and Berger SE (2006) Motor development. In: Damon W and Lerner R (eds.) *Handbook of Child Psychology: Vol. 2: Cognition, Perception, and Language*, 6th edn., pp. 161–213. New York: Wiley. Step length, distance between consecutive steps; Step width, lateral distance between steps; Foot rotation, absolute value of in/out-toeing from path of progression; Velocity, overall distance/time; Swing time, percent of gait cycle with one foot moving through the air; Double support, percent of gait cycle that both feet are on the floor; Vertical acceleration of the center of mass, rate of change in velocity of the center of mass along the vertical axis. Adapted from Bril B and Ledebt A (1998) Head coordination as a means to assist sensory integration in learning to walk. *Neuroscience and Biobehavioral Reviews* 22: 555–563, with permission from Elsevier. Curves for step length, step width, and foot rotation drawn from data presented in Adolph KE, Vereijken B, and Shrout PE (2003) What changes in infant walking and why. *Child Development* 74: 474–497, reproduced with permission from Blackwell publishing. Curves for velocity, swing time, and double support derived from data presented in Garciaguirre JS, Adolph KE, and Shrout PE (2007) Baby carriage: Infants walking with loads. *Child Development* 78: 664–680 and Garciaguirre JS and Adolph KE (2006) Infants everyday locomotor experience: A walking and falling marathon. *International Conference of Infant Studies*, Kyoto, Japan. Curve for vertical acceleration drawn from data presented in *Journal of Motor Behaviour* 24: 105–116. Reprinted with permission of the Helen Dwight Reid Educational Foundation. Published by Heldref publications, 1319 Eighteenth St, NW, Washington, DC 20036-1862. Copyright © 1992.

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. Although infants' average step length is short and average double support period is long relative to those of mature walkers, occasionally they can take steps longer than their leg length and display short periods with both feet on the floor.

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 walking onset: sufficient balance control to support the body on one leg while the other leg swings forward. In fact, infant walkers fall downward into each step; the vertical acceleration of their center of mass is negative when their foot contacts the floor. 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.

Since the early pioneers, researchers have debated the underlying factors that give rise to developmental improvements in balance control. 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. 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. Thus, infants require less strength to keep their bodies within the region of permissible postural sway. 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 detect the perimeter of their sway region. In addition, lifting their legs against gravity provides rigorous strength training in the leg muscles.

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 2 years of life, and neural fibers become increasingly myelinated in the corticospinal tract. Other psychological functions that require combinatorial sequences (language, symbolic play) appear at approximately the same age as walking. Infants' high-guard arm position co-occurs with a return to two-handed reaching, suggesting underlying brain linkages. In support of a body-based account, chubbier, more top-heavy infants tend to begin walking at later ages than slimmer, more maturely proportioned babies. Experimentally simulating more babyish body proportions and decreased strength by dressing infants in lead-weighted shoulder packs causes them to fall more frequently; when they manage to stay upright, infants wearing lead-loaded packs display less proficient walking patterns. 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 walking onset.

To date, the three putative underlying factors have only been pitted against each other statistically. When experience (indexed by the number of days since walking onset), brain changes (indexed by infants' chronological age), and body changes (measures of 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. Neither age nor body dimensions exert statistical effects above and beyond those produced by experience. However, the 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 weeks, then in the course of a single day, infants can grow up to 1.65 cm. New video-tracking measures of experience suggest that infants accumulate truly massive amounts of experience with balance and locomotion. A typical 14-month-old may travel the length of 39 football fields per day and incur 90 minor falls. Advances in understanding the relation 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 bi-directional nature of development. Both early pioneers and contemporary researchers agree that brain, body, and practice 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 infants' bodies.

Walking is the most recognized of infants' locomotor achievements, but it is not infants' final locomotor milestone.

Although new walkers can carry objects in their arms and loads in tiny packs on the back, front, and sides of their bodies, 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. 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.

Turning in circles and walking backward typically appear after forward walking. Jumping and running take even longer because, for both skills, both feet leave the ground simultaneously. Before infants can display a flight phase during running, they may Groucho run, where they speed-walk on bent knees like the famous actor, Groucho Marx. 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. 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 periods.

Cultural Effects and Historical Changes

The idea that infant locomotion is primarily the development of crawling and walking is an invention of twentieth century Western culture. 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. Mothers in Jamaica and Mali, for example, view crawling as dangerous, primitive, and unnecessary, and infants in these cultures are likely to skip crawling. To encourage walking, which they view as the outcome of training and exercise, caregivers submit their infants to daily massage and vigorous exercise routines consisting of stretching, massaging, stroking, and shaking (Figure 5). They throw newborns up in the air and catch them. They hold infants by an arm or leg, and support 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.

In accordance with cultural differences in mothers' expectations and childrearing routines, infants in Jamaica and Mali typically walk months earlier than infants in Western cultures. Similarly, mothers in Western Kenya exercise their infants' upright stepping and jumping movements and mothers in some East African tribes exercise their infants' prone postures; accordingly, infants in these cultures walk and crawl sooner than infants in cultures that do not exercise their infants' locomotor skills.

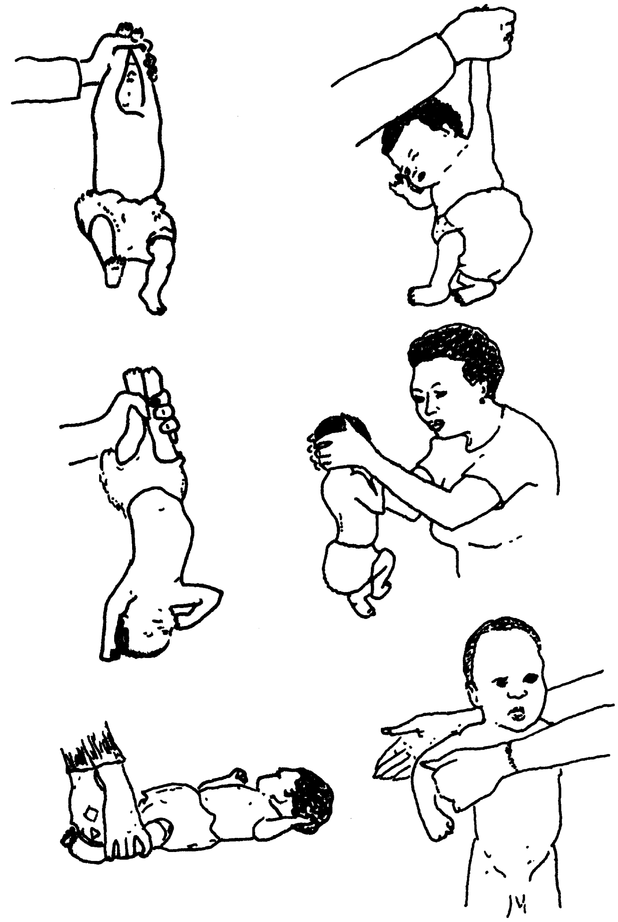


Figure 5 Some groups of African and Caribbean mothers engage in elaborate daily handling routines to massage and stretch their infants' muscles. These special exercises may contribute to the cultural differences in the ages at which motor milestones are achieved. From *Genetic, Social and General Psychology Monographs* Vol. 114, 379–408. Reprinted with permission of the Helen Dwight Reid Educational Foundation. Published by Heldref Publications, 1319 Eighteenth St., NW, Washington, DC 20036-1802. Copyright © 1988.

Even within a culture, historical changes in daily childrearing practices affect the structure and schedule of locomotor development. For example, in 1900, 40% of Western, middle-class infants skipped crawling. 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). Although doctors advise parents to give their waking infants 'tummy time', back-sleepers tend to fuss when they are placed prone. Among back-sleepers, more tummy time is related to earlier onset ages for sitting, crawling, and pulling to a stand, presumably because the prone position facilitates muscle strength in the arms and shoulders. Moreover, compared with infants who sleep on their stomachs, back-sleepers display more hitching, they sit, crawl, and pull to stand at later ages, and they score lower on measures of gross motor skill.

Beyond Muscles and Gravity: Locomotion in the Environment

How infants cope with gravity and inertia addresses only part of the story of locomotor development. Functional locomotion involves movement over variable terrain. In infants' typical environment, objects are strewn in the path. Changes in elevation create an up-and-down landscape. Ground surfaces can be high traction or slippery, rigid or deformable. The legacy of abstract stages from the early pioneers does not capture the embodied and embedded nature of locomotor development. As exemplified in Figures 6 and 7, a functional characterization of locomotor development illustrates 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 of infants' locomotor decisions.

Variations in Surface Layout

The most famous paradigm for testing infants' response to variations in the surface layout is the 'visual cliff' (Figure 6(a)), first devised by Eleanor Gibson and Richard Walk. The apparatus is a large glass table, divided in half by a narrow starting board. On the 'deep' side, a patterned surface lies on the floor far below the glass, creating the illusion of an abrupt drop-off. The 'shallow' side serves as an experimental control: The patterned surface is placed directly beneath the glass, providing visual information for a solid surface. Infants are placed on the center starting board and encouraged to cross by caregivers standing at first one side then the other. Animals descend from the starting board to the side of their choosing.

Since the initial report in 1957, dozens of experiments have yielded fascinating but conflicting findings regarding when and why human infants and other animals avoid locomotion over the deep side of the visual cliff. An early view was that adaptive avoidance responses depend on depth perception and that depth perception is innate. However, the problem is not lack of depth perception because human infants can see the drop-off months before they begin crawling.

A widely cited, but controversial claim is that infants avoid the apparent drop-off when they have acquired fear of heights and that fear, in turn, depends on the duration of infants' locomotor experience. However, behavioral indices of fear yield discrepant findings. For example, some researchers have found accelerated heart rate – a measure associated with fear – when crawling infants are lowered toward the deep side. However, other researchers found decelerated heart rate – a measure associated with interest – when crawling infants are lowered toward the deep side. Moreover, infants display positive or neutral facial expressions, not fearful expressions, when they avoid crawling over the apparent drop-off.

Findings are equally discrepant with regard to locomotor experience. Although some studies found that crawling experience predicts avoidance on the deep side, other studies showed the opposite result – that crawling experience predicts crossing onto the deep side. Longitudinal data are inconclusive because infants learn from repeated testing that the safety glass provides support for locomotion. In fact, infants who have prior experience playing with Plexiglas boxes, do not avoid crossing the visual cliff. In some studies, locomotor experience appears to be posture-specific: Crawling infants who avoid the deep side when tested on their hands and knees will readily cross when tested in an upright posture in a wheeled baby-walker. In other studies, locomotor experience appears to generalize: More 12-month-old walkers avoid locomotion over the deep side than 12-month-old crawlers.

Albeit the most famous test paradigm, the visual cliff is not optimal. Discrepant findings may result from methodological problems stemming from the design of the apparatus. The safety glass presents mixed messages: The visual cliff looks dangerous, but feels safe. In fact, because infants quickly learn that the apparatus is perfectly safe (albeit creepy), avoidance attenuates, and they can only be tested on one or two trials. 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.

To circumvent the methodological problems with the visual cliff, researchers have devised other paradigms with real drop-offs using apparatuses with adjustable dimensions and no safety glass (a spotter follows alongside

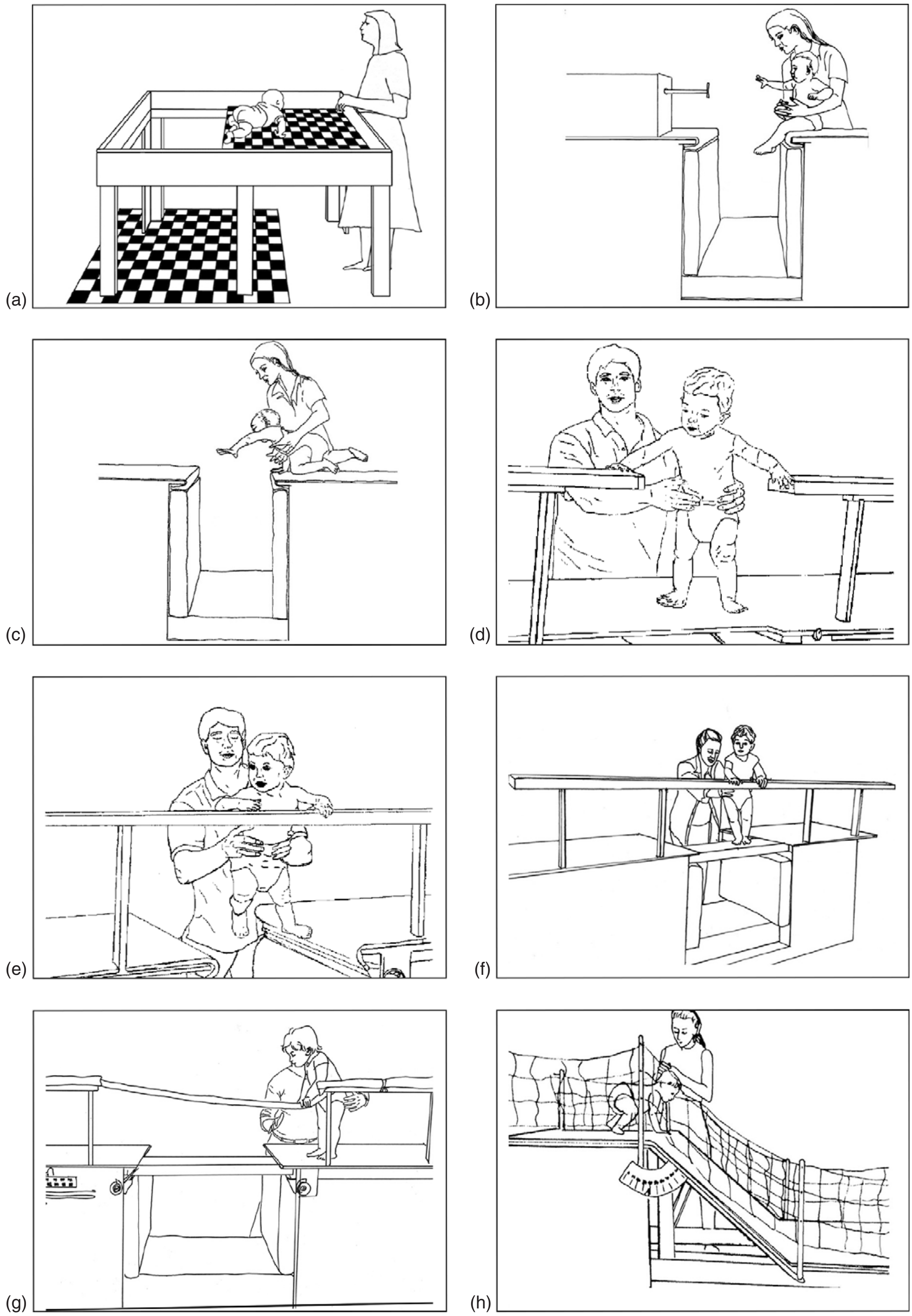
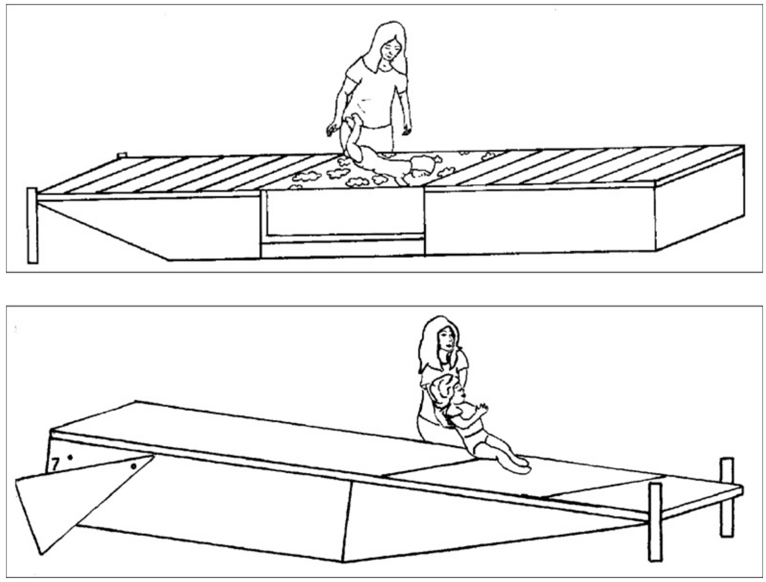


Figure 6 Illustrations of several paradigms for testing infants' locomotor decisions when challenged with variations in the surface layout. Figure partially adapted from Adolph KE and Berger SE (2006) Motor development. In: Damon W and Lerner R (eds.) *Handbook of Child Psychology: Vol. 2: Cognition, Perception, and Language*, 6th edn., pp. 161–213. New York: Wiley. (a) Crawling infant approaching an apparent drop-off on a visual cliff. From Walk RW and Gibson EJ (1961) A comparative and analytical study of visual depth perception. *Psychological Monographs: General and Applied* 75 (15, Whole No. 519), 1961, © American Psychological Association, adapted with permission. (b) Infant leaning forward over an adjustable gap in the surface of support in an experienced



(a)

(b)

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. Reproduced from Adolph KE and Joh AS (2007) Multiple learning mechanisms in the development of action. In: Woodward A and Needhan A (eds.) *Learning and the Infant Mind*. New York: Oxford University Press. By permission of Oxford University Press. (b) Infant slipping on a walkway interrupted by a low-friction Teflon floor. Courtesy of Joh AS and Adolph KE, New York University.

infants to ensure their safety). The gaps paradigm is one such alternative to the visual cliff (**Figures 6(b)** and **6(c)**). The apparatus challenges infants with a 'veritable cliff', a moveable platform abutting a deep precipice.

On the gaps apparatus, the duration of infants' everyday experience maintaining balance and locomotion predicts whether they avoid falling into the drop-off. However, learning does not transfer from an earlier developing postural control system to a later developing one. For example, at 9 months of age, most infants have been sitting for a few months, but have just begun crawling. In both postures, infants are encouraged to lean forward over the gap to retrieve a toy on the far side of the precipice. When facing gaps as experienced sitters, infants perceive precisely how far forward they can lean without falling into the precipice. However, when the same infants face the same gaps as novice crawlers, they show poorly adapted decisions: They fall into impossibly risky gaps on trial after trial, even on the widest, visual-cliff sized gap.

A similar pattern of results regarding the role of locomotor experience holds for other action systems and test situations. For example, at 11 months of age, most infants are experienced at cruising sideways along furniture but they have not yet begun to walk independently. When challenged with a gaps task relevant for keeping balance with their upper extremities as in cruising – a solid floor, but an adjustable gap in the handrail they are holding for support – their locomotor decisions are highly accurate: They attempt to cruise over safe gaps and avoid cruising over risky gaps. However, when challenged with a situation relevant for keeping balance with their lower extremities as in walking – a solid handrail, but an adjustable gap in the

sitting posture. Adapted from Adolph KE (2000) Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science* 11: 290–295 (c) Infant approaching an adjustable gap in the surface of support in an unfamiliar crawling posture. Adapted with permission from Adolph KE (2000) Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science* 11: 290–295. Copyright (2000) by American Psychological Society, with permission from Blackwell publishing. (d) Cruising infant deciding whether to span an adjustable gap in the handrail used for support. (e) Cruising infant deciding whether to span an adjustable gap in the floor. (d) and (e) Adapted from Adolph KE and Joh AS (2007) Multiple learning mechanisms in the development of action. In: Woodward A and Needhan A (eds.) *Learning and the Infant Mind.* New York: Oxford University Press. By permission of Oxford University Press. (f) Infant crossing narrow bridge using a handrail as a tool to augment balance. Berger SE and Adolph KE. Infants use handrails as tools in a locomotor task. *Developmental Psychology* 39: 594–605, 2003, Copyright © the American Psychological Association, reprinted with permission. (g) Infant deciding whether a wobbly handrail will aid in walking over a narrow bridge. Reprinted from Berger SE, Adolph KE, and Lobo SA (2005) Out of the toolbox: Toddlers differentiate wobbly and wooden handrails. *Child Development* 76: 1294–1307, Copyright (2005) by the Society for Research in Child Development, with permission from Blackwell publishing. Reprinted with permission. (h) Crawling infant at the top of an adjustable slope. Adapted from Adolph KE (1997) Learning in the development of infant locomotion. *Monographs of Society for Research in Child Development* 62(3, Serial No. 251), with permission from Blackwell Publishing.

floor – their locomotor decisions are grossly inaccurate: They attempt safe and risky gaps alike, despite viewing the obstacle at the start of each trial (see **Figures 6(d)** and **6(e)**). Newly walking 11-month-olds err in both conditions, as if they do not know how many steps they can take before reaching the ending handrail and they do not realize that they need a solid floor to support their bodies.

At 16 months of age, when most infants are experienced walkers, they use a handrail as a tool to augment their balance (**Figure 6(f)**). When encouraged to cross wide and narrow bridges spanning a deep, wide precipice, infants refuse to walk over narrow bridges on trials when a handrail is not available, but successfully walk over the same bridges when they can hold onto a handrail to keep balance. They run straight over wide bridges regardless of whether a handrail is available. When the substance of the handrail varies, infants walk over narrow bridges when the handrail is made of sturdy wood, and avoid crossing when the handrail is made of wobbly foam (**Figure 6(g)**).

In contrast to cliffs, gaps, and bridges that present an abrupt discontinuity in the visible surface texture, sloping ground is continuous between the summit and the base and infants can feel the intervening slope with their hands and feet (**Figure 6(h)**). In both cross-sectional and longitudinal studies using a slope paradigm, experienced crawling and walking infants display exquisitely fine-tuned prospective control of balance. As they approach the slope, they slow down, peer over the edge, probe the sloping surface by rubbing it with their hands and feet, and generate torque at the relevant joints by making small stepping and swaying movements and rocking back and forth with their hands or toes at the brink. On safe slopes, infants crawl or walk down. On risky slopes, they adopt alternative locomotor strategies (sliding down in sitting, backing, or prone positions) or avoid descent.

Experienced 14-month-old walking infants can even update their risk assessment after experimental manipulation of their body dimensions with a lead-loaded vest. While carrying lead loads in shoulder packs, infants' bodies are more top-heavy and immaturely proportioned. Infants recalibrate their judgments of risky slopes to their new, more precarious balance constraints. They correctly treat the same degrees of slope as risky while wearing the lead-weight shoulder packs but as safe while wearing the featherweight shoulder packs.

As in the gaps paradigm, infants require a protracted period of learning before demonstrating adaptive locomotor decisions on slopes, and experience with balance and locomotion is posture-specific. In infants' first week of crawling they repeatedly plunge headfirst down impossibly steep slopes. Over weeks of crawling, locomotor decisions gradually hone in to infants' actual ability. The decrease in errors reflects increased powers of calibration because, like the toddlers wearing lead-weighted shoulder packs, each week brings about naturally occurring changes in infants' body dimensions and locomotor skill. 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.

Learning to gauge threats to balance in a crawling posture, however, does not transfer to walking. Despite months of testing and hundreds of trials on slopes, the same infants who had avoided risky slopes as crawlers show no evidence of generalization after they begin walking. Errors are just as high in infants' first week of walking as in their first week of crawling, and learning is no faster the second time around. Learning is so posture-specific that new walkers who avoid descent of an impossibly steep slope in their experienced crawling posture plunge down the same slope moments later when tested in their inexperienced walking posture.

The evidence suggests that a protracted period of everyday locomotor experience facilitates learning to gauge novel threats to balance, not fear of heights. Experience traversing slopes is not required for adaptive responding. Few infants in everyday life have experience descending slopes on their own, and in the laboratory, infants in control groups matched for age and experience behave similarly to infants tested repeatedly on slopes. As on the visual cliff, fear does not mediate adaptive responding. Infants do not display fearful or negative affect as they approach the brink, regardless of whether they plunge down or avoid risky slopes (although they sometimes fuss after they fall).

Finally, similar results regarding experience are obtained in studies that do not involve falling from a height. For example, psychophysical assessments show that walking experience is a better predictor of infants' ability to step over barriers placed at different heights from the ground than infants' age and body dimensions. As in the gaps experiments, infants show specificity of learning between sitting and crawling postures when asked to reach around barriers in their path. When tested longitudinally, crawling infants reach around a barrier to retrieve a desired object while in a sitting position several weeks before they retrieve the object by crawling around the barrier. In studies with cross-sectional designs, 10- and 12-month-olds are more successful at retrieving objects from behind a barrier when they are tested in a sitting position than when they must detour around the obstacle by crawling. As in the slopes experiments, infants show specificity between crawling and walking postures when asked to learn a location based on repeated trips to their mothers' hiding place: Experienced crawlers fare better than younger novice crawlers and better than older novice walkers.

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 parameters, including different regions of permissible sway, key pivots about which the body rotates, muscle groups for balance and forward 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.

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.

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. 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. For example, on their first encounter with an unexpectedly squishy surface, 15–39-month-old children and young adults walk straight over a flat, rigid platform into a bumpy, deformable foam pit, and fall (**Figure 7(a)**). 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 all ages, participants gasp when they fall, indicating that the consequences were unexpected. Although 15-month-olds 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 15-month-olds approach an unexpectedly slippery surface – a large, white, shiny piece of Teflon – all of them fall on the first trial (**Figure 7(b)**). 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.

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 14-month-old falls 15 times an hour in the course of free play. 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 perfectly level, rigid, high-traction ground and they topple over when they turn their heads or lift an arm. Everyday experience may lead to learned irrelevance. 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. 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 their threshold is much shallower under slippery conditions than under high-friction conditions.

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.

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, and variations in the terrain. 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.

Thus, the development of locomotion reflects important changes across many domains of development – physical growth and biomechanics, as well as perceptual learning and cognitive development. For infants, carrying objects involves developmental changes in the biomechanics of balance. 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 dramatic examples of means-ends problem solving.

Moreover, the development of locomotion facilitates change across many domains of development. 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 Campos and colleagues remind us, travel broadens the mind.

Acknowledgments

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See also: Milestones: Physical; Motor and Physical Development: Manual; Perception and Action; Physical Growth; Reflexes.

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