6
MOTOR DEVELOPMENT

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Introduction: The Importance of Motor Development

Motor behavior is critical to developmental science. Regardless of researchers' interests, motor behavior and its development pervade every aspect of the discipline.

Movement as Behavior

For researchers interested in behavior, movement is the target of study (Adolph & Hoch, 2019; Adolph & Robinson, 2015; Rosenbaum, 2005). The possibilities for study are endless because all behavior is motor behavior. Every action involves movements of the face, limbs, or body—infants' first smiles and first steps, children's handwriting and soccer games, teens learning to drive or make a bed, young adults watching a movie or whisking an egg white, and older adults coping with the indignities of aging. Thus, for behavioral researchers, the types, forms, and performance of motor behaviors—from head to toe and across the lifespan—are intrinsically interesting topics of research.

Movement as a Partner With Psychophysiology

For researchers interested in basic psychological functions or neurophysiology, movement is an integral component (Krakauer et al., 2017; Maselli et al., 2023). Every movement gives rise to perceptual information, and perception, in turn, guides actions adaptively (Bertenthal & Clifton, 1998; Bornstein et al., in this textbook; J. Gibson, 1979). Movements can also provide the grist for cognition, input for social interactions, and support for emotions and motivation, and each of these psychological functions—and all the underlying neurophysiology—can influence motor behavior.

Moreover, motor development cascades and reverberates across psychological domains—perception, cognition, language, social interaction, and emotion (Adolph & Hoch, 2019; Adolph & Robinson, 2015; Campos et al., 2000; E. Gibson, 1988; Piaget, 1952). Burgeoning motor skills open up new worlds for learning and doing, and reciprocally, decrements in motor skills due to disability or aging constrain possible behaviors (Shumway-Cook et al., 2023).

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Movement as an Informant of the Mind

For researchers interested in unobservable aspects of the mind, movements are a critical tool (Adolph & Froemke, 2024; Maselli et al., 2023). Motor responses—speech, button presses, points, looking behaviors, and so on—are a primary medium for researchers' inferences about mental activities such as thoughts, percepts, feelings, and intentions. Simple movements like a button press or shift in eye gaze can convey thought processes more quickly and reliably than spoken words.

Other tools, such as neuroimaging or physiological responses, can be ambiguous informants about mental activity, especially when used in isolation. For example, neural activation in the same brain regions can have different causes across development (Johnson, in this textbook). Thus, patterns of neural activity have more explanatory power when coupled with overt motor behaviors (Blumberg & Adolph, 2023).

Movement as a Consequence of Context

For researchers interested in the effects of context on behavior or mind, motor behaviors (and all the accompanying percepts, thoughts, plans, and emotions) are contextualized in a body moving in an environment shaped by a culture (Adolph & Hoch, 2019; Adolph & Robinson, 2015; Gomez-Marin & Ghazanfar, 2019). Movements depend on and exploit the physical properties and biomechanical constraints of the body in real-time and over development. The body is always embedded in a physical environment that can constrain or facilitate behavior. Indeed, at every point in development, motor behavior must be geared to the immediate environment—reaching must be adapted to object distance and properties, locomotion must be adapted to the features of the ground surface, and so on. With the advent of new motor skills, disability, or aging, the effective environment changes and provides a new set of constraints and possibilities (E. Gibson, 1988).

Movement is also enculturated (for reviews, see Adolph & Hoch, 2019; Adolph et al., 2010; Adolph & Robinson, 2015; Bril, 2018). It occurs in social, cultural, and historical contexts that reflect childrearing practices, people's expectations, and cultural norms (Amir & Bornstein, in this textbook). Most work on motor development, like most work in developmental science, focuses on only a small subset of the world's population. But even within a culture and historical period, the effects of enculturation are readily apparent. Differences in childrearing practices (how caregivers hold, dress, and exercise their infants), everyday activities, and norms affect the ages when motor skills first appear and the form of the behaviors across the lifespan (Bril, 2018; Karasik et al., 2015).

Movement as a Window Into Change

Finally, for researchers interested in change processes, motor behavior is an easily observable marker of change. Movements expose the emergence of new forms of behavior and reveal changes in behavior due to moment-to-moment contingencies and learning, development, and rehabilitation.

Perhaps most important for developmental science, motor behavior provides a uniquely rich and amenable model system for understanding general processes of change in people and nonhuman animals (Adolph & Berger, 2006; Adolph & Robinson, 2015; Gesell, 1946; Thelen & Smith, 1994, 1998). Because movements have a form and tangible structure, they provide a clear window into change processes that may hold for other topics of interest to developmental researchers that are formless and intangible—psychological functions such as cognition, emotion, and language.

Chapter Overview

Given the tremendous breadth of motor behavior in developmental science, this chapter aims to illustrate important aspects of motor development across the lifespan, rather than to provide a comprehensive review. The focus is on basic motor skills such as speaking, reaching, sitting, and walking and on how contextual influences of the physical, social, and cultural environment can lead to striking differences in such "universal" skills between people within and across cultures and historical time periods. A common theme across the chapter is the critical role of experience in motor development. People must move to learn how to move. And context shapes the practice regimen.

The chapter begins with spontaneous movements, which predominate the fetal and newborn periods and continue across the lifespan. As illustrated in Figure 6.1, the bulk of the chapter is organized around five functional action systems—posture, looking behaviors, facial actions, manual actions, and locomotion (Adolph & Franchak, 2016; Newell, 2020; Reed, 1982). Generally, functional actions are tied to particular body parts (e.g., eyes for looking, hands for manual actions), but other body parts contribute (e.g., whole body for looking) and, in some cases, take over the functions (e.g., feet for manual actions, arms for locomotion). Because actions are goal directed and geared toward function, each action system is intimately tied to perception. Each section of the chapter pays particular attention to infancy because that is the period when the foundation for each action system is laid down.

Spontaneous Movements: From Head to Toe

Many movements across the lifespan are produced spontaneously during wake and sleep without any goal or eliciting stimulus (Figure 6.1A). Spontaneous movements occur in every body part in every action system—including twitches, tics, stereotypies, brandishing the arms or flaring the nostrils while speaking, and so on. Despite the lack of intention, spontaneous movements are still coupled with perception and may serendipitously serve important developmental functions.

Spontaneous Movements in the Fetus

Motor behavior emerges as spontaneous movements in the fetus. The transformation from a single cell into a wriggling baby presents the most remarkable example in all of human development of the emergence of new behavioral forms.

Human fetuses begin moving as soon as they have the primitive neural circuitry to activate their rudimentary muscles and partially formed body parts—about 5 to 6 weeks post-conception (de Vries et al., 1982; Einspieler et al., 2021; Luchinger et al., 2008). The first fetal motor behaviors are quick whole-body startles and slow writhing movements (Einspieler et al., 2021). Limb movements appear between 7 and 10 weeks post-conception, around the same time as the limb buds begin to resemble arms and legs (de Vries et al., 1982). Vigorous leg kicks can somersault the fetus through the amniotic fluid, and hiccups

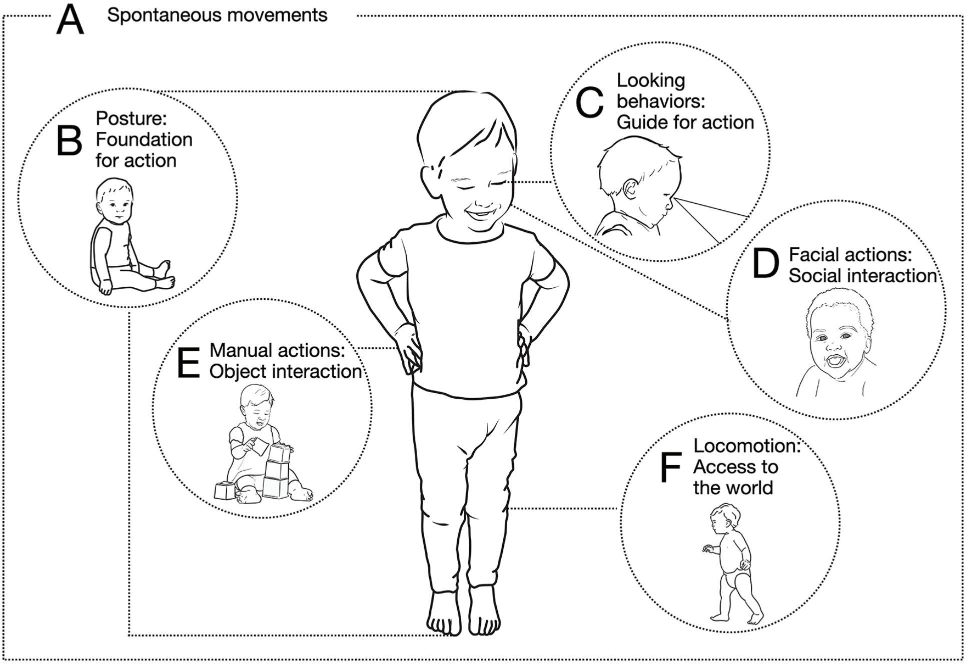

Figure 6.1 Motor behavior: spontaneous movements (dotted rectangle) and the primary functions of five action systems (dotted circles). (A) Spontaneous movements are produced without any goal or eliciting stimulus (e.g., twitches, tics, stereotypies) and occur in every body part. (B) Posture—the ability to resist gravity, support body weight, keep balance, and orient the body appropriately—provides the foundation for all other action systems. (C) Looking behaviors (eye movements typically accompanied by head, torso, and body movements) perceptually guide every action, including subsequent looking. (D) Facial actions. Movements of the face support emoting, vocalizing, speaking, and eating—all important behaviors for social interaction. (E) Manual actions such as touching, reaching, grasping, and manipulation are geared for physical interactions with something else, like objects, surfaces, or bodies. (F) Locomotion provides access to the world by moving the whole body from one location to another. The five functional action systems in this figure are shown connected to the body parts that typically perform the actions (e.g., hands for manual actions, legs for locomotion), but other body parts often support or even take over the functions of each system. Each action system contributes to life itself (e.g., looking to locate food, locomotion to bring the body to a source of food, manual actions to bring food to mouth, eating) and to the functions of other action systems.

Source: Drawings are reprinted with permission from the NIH Baby Toolbox (center, B, F) and from Kelsey West (C, D, E).

can move the whole body up and down (Prechtl, 1986). As appendages and digits appear, fetuses wiggle toes and fingers and form a fist.

Many arm movements are not random forays into the murk. By 12 weeks, two-thirds of fetal arm movements are toward objects in the uterus—the uterine wall, the umbilical cord, and the face and body (Sparling et al., 1999)—often in repetitive bouts, like fetal versions of Piaget's (1952) circular reactions (Bjorklund & Darby, in this textbook). By 26 weeks, half of fetal hand-to-face movements are hand to mouth (Myowa-Yamakoshi & Takeshita, 2006). Fetuses open their mouth before, not after, the hand arrives at the mouth (Reissland et al., 2014), suggesting that the movements are intentional, anticipated, and perceptually guided.

As body parts form and differentiate, various types of movements proliferate until about 18 weeks conceptional age, when fetuses have displayed most of their movement repertoire (Prechtl, 1988). The frequency of limb and body movements increases, peaking at 12 to 16 weeks post-conception (Kuno et al., 2001), and then decreases as the growing fetus fills up more and more of the uterine space (DiPietro et al., 2002; Ten Hof et al., 2002). Ironically, mothers become aware of fetal limb movements between 14 and 20 weeks (Kuno et al., 2001), about the same time when fetal movements begin to decrease due to cramped space in the uterus (de Vries & Hopkins, 2005). What mothers call "kicking" at this point is most often arm movements and partial leg movements because now the limbs are hemmed in by the uterine wall.

Head and face movements begin at 8 to 9 weeks post-conception with head turns, nods, opening and closing the jaws, and breathing movements from contracting the diaphragm (de Vries et al., 1985). By 9 to 10 weeks, mouth movements include yawning, sucking (thumb or fingers), and swallowing amniotic fluid (de Vries et al., 1982). By week 18, fetuses move all the parts of the face—including wrinkling the forehead, raising the eyebrows, and moving the lips and tongue (Nilsson & Hamberger, 1990). Fetuses produce recognizable smiles, grimaces, tongue protrusions, and yawns and adult-like expressions of laughter, crying, and pain (Azumendi & Kurjak, 2003; Reissland et al., 2011, 2013). After 23 weeks, fetuses open and close their eyes. In fact, all the muscles of facial expression are formed and innervated prior to birth (Oster, 2014).

Fetal movements serve important developmental functions (Einspieler et al., 2021). Some movements are adaptations to life in the womb: Swallowing amniotic fluid, for example, regulates water balance in utero (Moore & Persaud, 1993). Some movements are preparations for birth: Leg kicks help turn the fetus to a head-down presentation (Prechtl, 1986). However, most fetal movements function to jumpstart a developmental cascade. They support long-term outcomes by facilitating the physical development of lungs, muscles, bones, joints, and skin (Moessinger, 1983); providing perceptual experiences that shape neural development (Anderson & Thomason, 2013); and laying the groundwork for intentional action.

But why do fetuses move? Fetuses cannot possibly know that their movements will support development. Clearly, some movements are in response to external stimulation such as a loud sound from outside (de Vries & Hopkins, 2005) or the touch of a neighboring twin in utero (Piontelli, 2010), or to self-stimulation such as touching the face. But many fetal movements are a spontaneous product of the central nervous system with no proximal elicitor or goal (Hadders-Algra, 2007). Regardless of the reason, fetal movements cannot be rigidly programmed because dramatic changes in the shape and size of the fetal body require the central nervous system to alter the pattern of muscle activations to produce the same movement (Robinson & Kleven, 2005). Consider fetal hand-to-face behavior. The arms of a young human fetus are so short that the elbow must straighten to bring the hand to the face. Toward the end of gestation, arms are much longer, so fetuses must bend their elbows to bring the hand to the mouth. A completely different set of arm muscles is involved.

Spontaneous Behaviors in the Newborn and Beyond

Most newborn movements have been practiced for months by the fetus (de Vries & Hopkins, 2005). Nonetheless, newborns bear the imprint of being crunched for weeks in the tight confines of the uterus. Their limbs are tightly flexed in the "fetal position," with arms and knees drawn up to the chest (DiMercurio et al., 2022). Flexor muscles that bend the arms and legs are so strong and extensor muscles that straighten the limbs are so weak that adults must apply strong pressure to fully extend newborns' arms and legs, and when the limbs are released, they spring back into their bent positions. Moreover, the environmental context for movement is radically different for the fetus versus newborn. Out in the world, movements are no longer hampered by the encroaching walls of the uterus. But without the buoyancy of a fluid-filled environment, newborns begin extra-uterine life nearly prisoners of gravity. Each limb movement and change in body posture is a struggle. The ability to exploit gravitational forces appears later with motor skill acquisition, and for older adults, gravity is again the archenemy of movement.

Like those in fetuses, many newborn movements—both awake and asleep—are spontaneous, without an external stimulus or tangible goal (Figure 6.1A). Nonetheless, such movements can support development. While babies sleep, spontaneous twitches in their eyes, face, limbs, and digits help to build somatosensory maps in the brain (Sokoloff et al., 2020).

Differences in the quality and frequency of spontaneous, whole-body writhing and fidgety movements in early infancy are among the best behavioral predictors of cerebral palsy and other developmental motor disorders (Marschik et al., 2017; Reich et al., 2021). Likewise, repetitive bursts of movements such as rocking and hand flapping can be a sign of pathology such as autism (West et al., 2019). But rocking, hand flapping, and other stereotypies (kicking the legs in alternation, thumping a foot repeatedly against the ground, banging the arms, pulsing the tongue in and out of the mouth, etc.) are also common in healthy waking infants (Piek & Carman, 1994; Thelen, 1979). By the time infants are 12 months old, they have likely experienced over 110,000 bouts of wiggles, waves, kicks, and flaps in their arms, legs, heads, and trunks. Such well-practiced spontaneous movements can be incorporated into intentional actions—infants' airborne arm flaps and bangs of hands to a surface reappear as banging objects and later hammering (Karhs & Lockman, 2014).

Many spontaneous movements are the byproduct of spontaneous neural activity. The fleeting "gas smiles" of sleeping neonates are not actually due to gas but to spontaneous subcortical activity (Messinger, 2008). Likewise, the rapid eye movements and facial twitches of sleeping infants are generated subcortically (Sokoloff et al., 2020). After infancy, twitches during sleep are largely limited to rapid eye movements. Involuntary facial tics include vocalizations and speech. Tics typically appear in childhood and are indistinguishable in form from intentional movements (Ganos et al., 2019). However, even in young infants, spontaneous eye and face movements are not random or disorganized; infants display only a small fraction of all possible configurations (Oster, 2005). With age, spontaneous movements use more parts of the face in unison and increase in frequency and speed (Green & Wilson, 2006).

At first blush, some newborn movements appear to be reflexive responses to eliciting stimuli such as the sucking reflex in response to an object in the mouth, the asymmetric tonic neck reflex in which the head turns in the direction of an outstretched arm (like a fencing posture), and the stepping reflex when the baby is held upright with the feet on a surface (Gabbard, 2021). However, these sorts of newborn behaviors do not have the characteristics of a spinal reflex—that is, automatic, hard-wired, unmodifiable responses to an eliciting stimulus, like withdrawing your hand from a hot stove (von Hofsten & Rosander, 2018). Infants produce the behaviors with no eliciting stimulus. For example, young babies produce alternating leg movements characteristic of the so-called stepping reflex with their feet dangling in the air (Barbu-Roth et al., 2014) and while lying on their backs (Thelen, 1979). The behaviors are not impervious to cortical influences because infants "step" more when they are aroused (Thelen et al., 1984) or when they are exposed to visual flow information for movement (Barbu-Roth et al., 2014; Moerchen & Saeed, 2012).

Moreover, these so-called "reflexive" behaviors are modifiable. Newborns intentionally alter their sucking movements to hear a preferred sound or to view a preferred scene when the contingencies are arranged experimentally (DeCasper & Fifer, 1980; Kalnins & Bruner, 1973). Likewise, if newborns can only view their outstretched hand on a video monitor located on the opposite side of their body, they turn their heads in the direction of the video monitor, not in the direction of their outstretched hand (van der Meer et al., 1995). Similarly, infants kick their legs in whatever prespecified pattern (single-leg kicks, simultaneous kicks, or alternating kicks) causes an overhead mobile to jiggle (Rovee-Collier et al., 1978; Sargent et al., 2014; Thelen, 1994; Watanabe & Taga, 2011).

Summary

Spontaneous movements appear nearly as soon as fetuses have body parts to move, and such movements continue throughout the lifespan. Unintentional, spontaneous movements can serve important functions. In particular, earlier spontaneous movements lay the groundwork for later intentional movements. Experience practicing movements leads to improved performance, and experience begins prenatally—think how many times babies practice bringing the hand to the mouth, even before birth (Zoia et al., 2013). From the start, movements are always contextualized, first in a buoyant and then in a cramped uterine environment, and then, for the rest of life, outside in the world. Also from the start, perception and action are intimately linked such that behavior can be adapted to the constraints of the body and environment.

Posture: The Foundation for Action

You can lie flat on your back and move your eyes and mouth, but every action involving the head, torso, and limbs entails coping with gravitational forces. Enter postural control (see Figure 6.1B). Posture is the most foundational motor action because other actions are not possible without the ability to resist gravity, keep balance, and orient the body appropriately (Adolph & Franchak, 2016; Bernstein, 1967; Reed, 1982).

Head Control

The developmental triumph over gravity starts at the head. Head control provides the foundation for looking around, swallowing to eat or drink, and social interactions with others. Initially, newborns' heads flop in every direction as soon as they are lifted from the crib mattress (Bly, 2011). Thus, in many cultures, caregivers hold newborns like they are a fragile carton of eggs and provide continual support of their newborn's head. However, in cultures where caregivers hold their newborns more roughly, without supporting the head, babies acquire head control at earlier ages (for review, see Adolph et al., 2010). By 3 months, infants are sensitive to the routine of being picked up by a caregiver and stiffen their head and neck as the caregiver's hands approach and begin to lift (Fantasia et al., 2016).

Typically, postural control gets off the ground after infants can lift their heads while lying on their bellies. The ability to hold the head up while propped on the forearms appears around 3 months of age (like a “low cobra” posture in yoga). By 5 months or so, infants can shift their weight from one arm to the other (Bly, 2011), thereby freeing a hand to reach for and manipulate objects (Soska & Adolph, 2014).

Historical and cultural differences in caregivers’ placement of infants into prone postures leads to differences in how much practice infants get with prone balance control. Among Western caregivers, the widespread generational switch from putting infants to sleep on their backs instead of their bellies to prevent sudden infant death syndrome led to later onset ages for prone propping and rolling—presumably because infants get less prone practice just before they fall asleep and right after they wake up (for reviews, see Adolph & Hoch, 2019; Adolph et al., 2010).

Sitting and Standing

Upright sitting and standing provide the basis for actions performed in a stationary position such as using the arms to grasp and manipulate objects and head and eyes to look around. Upright postures are so critical that people of every age habitually supplement postural control by using their hands and external supports like a banister for balance.

To sit independently with legs outstretched on the floor requires control over the entire trunk. Wobbly infants initially solve the problem by propping on their arms between their outstretched legs. Sitting on a bench or chair with legs hanging freely requires infants to cope with a reduced base of support, so trunk control is even more critical. Sitting on a squishy or slanted surface (such as a caregiver’s lap) requires infants to lean their trunk forward or backward to keep their torso within the base of support.

Bit by bit, infants gain control over all the segments of their spine, from neck to hips, one segment of vertebrae at a time (Rachwani et al., 2023; Saavedra et al., 2012). At first, infants’ heads flop when they are held under the armpits in a sitting position. After babies can balance their heads between their shoulders, their backs crumple when they are held at the waist. After infants can keep a straight back, they still fall, chest to knees, unless held at the hips or propped on their arms. Finally, between 6 and 8 months of age, infants can maintain their center of mass within the base of support provided by their bottoms and outstretched legs. Moreover, nearly as soon as infants can sit independently, they perceive the constraints imposed by the properties of the ground surface. They adjust the direction and angle of their torso by leaning forward or backward in accordance with the direction and slope of the floor beneath their bottoms (Rachwani et al., 2017).

Caregivers implicitly recognize their infants’ level of spinal control by holding their sitting babies at the level of infants’ torsos where external support is needed (Duncan et al., 2018). Clinicians measure postural control in infants and children by assessing their level of spinal control, and clinicians intervene by providing the just-right level of spinal support in children with disabilities (e.g., cerebral palsy) to enable manual actions and social interactions, while encouraging children to push their limits (Saavedra et al., 2010).

Standing is more challenging than sitting. The base of support is smaller, and standing requires sufficient strength to prevent all the gravity-opposing body parts from neck to ankle from collapsing (for reviews, see Ivanenko & Gurfinkel, 2018; Whitall & Clark, 2018). To augment leg strength and balance, infants first stand propped against furniture using their arms for support. Later, at about 11 months of age, infants stand independently.

In cultures where caregivers encourage and exercise sitting and standing, infants sit and stand independently at younger ages (for reviews, see Adolph & Hoch, 2019; Adolph et al., 2010). For example, 5-month-olds in Cameroon and Kenya can sit independently for 20 minutes, whereas most 5-month-olds in Italy, Argentina, Korea, and the United States can sit independently for less than 1 second (Karasik et al., 2015). Conversely, in cultures where caregivers constrain infants' practice with sitting and standing, infants acquire those skills at older ages (Adolph et al., 2010). In Tajikistan, infants spend large portions of the day and night bound supine, neck to ankles, in a special cradle, and as a consequence, they sit, stand, crawl, and walk weeks to months later compared with cultures that do not constrain infants (Karasik et al., 2023). Caregivers across the United States and among traditional forager-horticulturalists in rural Papua New Guinea decrease their time holding and carrying infants as their babies acquire sitting, standing, and locomotor skills, suggesting that caregiving behaviors are attuned to infants' growing postural control (Franchak, 2019; Tracer & Wyckoff, 2020).

Every culture encourages positions for sitting that differ based on etiquette, gender, social hierarchies, religious practices, work and sport practices, and so on (Bril, 2018; Hewes, 1955). Due to years of practice, older children and adults may sit in postures such as deep squats (buttocks to heels) or prayer poses (knees bent beneath the body, or crisscrossed for meditation) that defy people in cultures that do not encourage those postures.

Anticipating and Reacting

"Stationary" postures such as sitting and standing are not really stationary. In any posture that defies gravity, the body is continually in motion, swaying slightly within its base of support (Saavedra et al., 2012; von Hofsten & Rosander, 2018). Thus, balance is always tenuous, and any change in forces or perceptual information can disrupt balance. Posture relies on perceptual information to anticipate and to react.

Postural control must be anticipatory because every movement of the extremities changes the forces acting on the body (von Hofsten & Rosander, 2018). Lifting an arm to reach for an object, wave goodbye, or open a drawer while sitting requires the torso to anticipate and prepare for the destabilizing forces due to lifting the arm. Doing the same while standing requires anticipatory stabilization of the entire posture—first in the legs, then the trunk—before moving the arm (Shumway-Cook et al., 2023). Preparing to take a step requires the anticipation of destabilizing forces (Mani et al., 2021). Infants, young children, and elderly adults show less anticipatory control than young adults because babies must learn which postural control strategies are effective and elderly adults do not execute the control strategies fast enough to offset the destabilizing forces of the limb movements (Shumway-Cook et al., 2023). Postural control must also anticipate the next movement in a sequence. The head and trunk must turn, for example, to get the eyes on a target to one side of the body, so as to plan which arm to move for reaching (Rachwani et al., 2019). New sitters try to keep their bodies rigidly upright because leaning to one side or even turning their heads or extending an arm can overtax anticipatory balance control (Rachwani et al., 2013, 2023).

Postural control must also be reactive in response to new information. At the most basic level, to keep balance, a body sway in one direction must be followed by a compensatory sway response in the opposite direction (for reviews, see Adolph & Berger, 2006; Whitall & Clark, 2018). Multiple sources of perceptual information specify the body's position as it sways within the base of support: haptic information from stretching and deformation of the skin on the feet, proprioceptive information from muscles and joints in the legs, accelerations detected by the vestibular system, and optic flow available to the visual system. Across the lifespan, a gentle touch on a handrail, a moving rod, or even a flimsy curtain increases postural control by providing a new source of tactile information about the body's location in space (Whitall & Clark, 2018). At every point in development, standing is easier with eyes open than closed because vision augments vestibular and muscle–joint information for postural control (Shumway-Cook et al., 2023; Verbecque, Vereeck, & Hallemans, 2016). Likewise, across the lifespan, standing is easier on a firm, wide surface than on squishy foam or crosswise on a narrow beam because compensatory ankle movements can more effectively resist forces on a firm, wide surface.

Normally, the multiple sources of information are in concert. But when visual motion information is pitted against other sources of information by moving the walls of the room while the floor is stationary, optic flow trumps the others (J. Gibson, 1979). The sensation is akin to when passengers in a stationary train see a moving train outside the window. Participants erroneously "see" that they are moving but correctly feel that they are stationary. The sensation of induced sway is so compelling that children and adults respond with compensatory sways. Infants often overcompensate such that they stagger and fall. Likewise, when the floor unexpectedly moves beneath their feet, infants and young children stagger and take steps, whereas older children and adults respond by rotating around their ankles or knees (for review, see Adolph & Berger, 2006).

Moving Between Postures

Posture is only functional when people can move between postures at will—rolling over to get out of bed, standing up from sitting on a chair, toilet, or floor, crouching or sitting down from a stand, and so on. Even something as seemingly simple as switching between standing and walking is fraught with complexities because the body must transition between stationary and dynamic postural control (Mani et al., 2021; Zhao et al., 2021). For example, despite the intention to move, patients with Parkinson's disease suddenly feel that their feet are glued to the ground, and they are frozen in place (Gao et al., 2020).

Around 5 months of age, infants learn to transition between belly and back. Often the initial flips are prompted serendipitously by the effort to reach for an object. Between 7 and 9 months of age, after infants can sit and crawl, they learn to push themselves backward from hands and knees into a sitting position and to transition from sitting to hands and knees without an intermediate belly flop (Adolph et al., 1998). Later, infants learn to pull themselves upright to a stand, first from a crawling position and then through a half-kneeling, "marriage-proposal" position (Atun-Einy et al., 2012). Across infancy (and likely across the lifespan), sitting and standing are the two most common postures and the two most common postural gateways to other postures (Franchak, 2019; Thurman & Corbetta, 2017, 2020).

Getting upright from the floor without external support appears around the time when babies can walk independently. To stand up from supine, babies first roll off their back, then move from a crawling posture to a "downward-dog" posture (with hands and feet on floor, bottom toward the ceiling), and then work their way upright (Marsala & VanSant, 1998). At older ages, children can forego the roll and sit up from supine and then get their feet beneath their bodies by squatting or kneeling (VanSant, 1988). The most advanced children do it without using their hands. Getting up becomes so efficient and commonplace that toddlers can return to play within 2 seconds after an inadvertent fall to the floor (Han & Adolph, 2021). In contrast, children with disabilities such as cerebral palsy and elderly adults may require several minutes to transition from the floor to upright, or they might not be able to rise at all. The ability to transition between sitting on a chair and standing upright is so critical and frequent (60 times per day, on average, for healthy adults) that the timed get-up-and-go test is a common diagnostic and therapeutic intervention for clinicians working with patients to restore daily function (Dall & Kerr, 2010; Podsiadlo & Richardson, 1991; Verbecque, Vereck, et al., 2016).

Summary

Postural control underlies all actions of the head, torso, and extremities. Thus, developmental changes in postural control across the lifespan affect access to the environment for exploring and doing things with objects, places, and people (Franchak, 2020; E. Gibson, 1988). The development of postural control in infancy and childhood is largely a process of achieving increasingly upright postures with an increasingly small base of support, learning to transition quickly and efficiently between postures at will, and learning to use external supports for posture when needed. But cultural differences in formal and informal caregiving practices affect the form and developmental timing of postures. Postural control in middle age, elderly adults, and people with disabilities involves accommodations to impairments in muscle strength, joint and spine flexibility, and perceptual control of anticipatory and reactive behaviors.

Looking Behaviors: Visual Guidance of Action

Looking around requires eye movements, and visual information from looking guides every action system, from posture to facial actions to manual actions and locomotion (Figure 6.1D). Looking also guides subsequent looking.

Looking

For humans, vision is the primary way to access information about the environment, and vision is essentially a motor behavior. Seeing entails looking—by directing the eyes at targets, tracking interesting events, and visually exploring a scene (Bornstein et al., in this textbook; J. Gibson, 1979; von Hofsten & Rosander, 2018).

People see best when images fall on the small, foveal region in the center of the retina. Thus, to see clearly, people direct their gaze to the target of interest. Visual exploration by scanning a stationary scene involves quick, jerky, saccadic eye movements. Saccades are the fastest movements produced by the human body. Tracking a moving target requires smooth pursuit, so that eyes (and head) move along with the target. To see objects in depth, the eyes converge or diverge. If the head and/or body are moving, the eyes must make compensatory movements to stabilize gaze. Even keeping the eyes fixated on a target is not a passive or resting process; drifts in fixation must be detected and corrected (think of threading a needle).

Although vision only requires moving the eyes, looking is typically a whole-body affair (J. Gibson, 1979; Hayhoe, 2018). Head movements bring the eyes to the desired part of visual space, and movements of the torso place the head in an optimal position for looking.

Thus, visual perception is really a perception–action system that requires perceptual information to guide looking adaptively.

The First-Person View

Head-mounted eye tracking allows researchers to record the first-person perspective of the world in freely mobile infants, children, and adults (Franchak, 2017). Looking while freely mobile is more representative of real-world visual exploration and guidance of action than looking at a screen or still image with the head or body fixed in place (Franchak & Yu, 2022).

One important finding revealed by head-mounted eye tracking concerns looking at faces. During natural activity, adults frequently look at their children's faces (Franchak et al., 2018; Yurkovic-Harding et al., 2022). But infants and young children rarely look at their caregivers' face, even when caregivers talk to them or show them objects (Franchak et al., 2018, 2011; Smith et al., 2011). Young children with autism do not look at their caregivers' face (long considered a diagnostic symptom of autism), but neither do same-age neurotypical children in the same situations (Adolph & West, 2022; Yurkovic-Harding et al., 2022). Infants and young children look most at objects and surfaces and at their own or other people's hands holding objects. Face-looking is also culturally dependent: In some cultures, it is rude to look directly at the face of a conversational partner or stranger. In other cultures, it is rude not to look (Gobel et al., 2017).

A second important finding is that much of looking is serendipitous: It is a byproduct of the viewing posture, vantage point, and body movement. Infants look at objects because manual actions bring objects into the field of view (Franchak et al., 2011; Smith et al., 2011). While crawling, infants look primarily at the ground because they cannot crank their necks upward to look around the room (Kretch et al., 2014). Walking infants, children, and adults do not need to direct gaze at obstacles to navigate them safely; they typically rely on information from the periphery of their visual field (Franchak & Adolph, 2010). However, walking infants have a higher rate of obstacle fixation than older children and adults because they are shorter, so the lower bound of their visual field is closer to their feet. But attention can trump vantage point: When infant and caregiver vantage points are equated by carrying infants in a forward-facing carrier on caregiver's chest, infants look at different things from their caregivers (Kretch & Adolph, 2015).

Perhaps the most important finding from head-mounted eye tracking is that looking supports motor planning. As Sullivan et al. (2021, p. 2) put it, "the eye leads behavior." As adults perform one action in a sequence (cooking, walking, driving, reading, putting together a camping tent, etc.), they look ahead to the next action in the sequence. Experience with the tasks of one's culture and historical milieu in the context of the physical surroundings tells people where to look to guide their actions (at the icons on a computer screen, words on a page, oncoming traffic and bends in the road, and so on).

Because looking itself is a motor action, it also requires planning—a continual loop of planning to plan (Ossmy et al., 2020). Adults, for example, know to point their eyes at a hammer prior to grasping, so they first generate the required visual information about the orientation of the tool relative to their reaching hand, then their brains register the information, and finally they grasp the handle of the tool appropriately. Children, in contrast, often begin to reach before they get their eyes on the target, and thus the whole cascade of behavioral and neural events goes awry (Ossmy et al., 2022). Children must learn to point their eyes to relevant parts of a scene to guide their actions adaptively, and prior experience with visually guided actions teaches them which parts of the scene are relevant.

Summary

Across the lifespan, looking around is people's primary way to access the larger environment. Looking is also critical to guide postural, facial, manual, and locomotor movements, and experience with visual guidance of action guides looking behavior. Like any action, looking to the correct target requires planning, often based on prior looks. Moreover, looking supports social interactions by establishing engagement and providing information about others' behaviors, emotions, and thoughts. Postural transitions and locomotion support looking by putting people's eyes in the right place, and manual actions support looking by bringing the object to people's face.

Facial Actions: Social Interactions With Others

Movements in the face—for emoting, speaking, and eating—are the motor behaviors most critical for function in a social world (see Figure 6.1C). Indeed, from newborn to older adult, facial movements are both life sustaining and life enriching.

Emoting

Every facial expression is the result of muscle actions—typically many muscles involving the mouth and eyes. A simple smile, for example, involves only the zygomaticus major muscles to raise the corners of the lips. But a full Duchenne smile (named after the physician who first studied smiling movements) also involves the orbicularis oculi to raise the cheeks, squint the eyes, and crinkle the skin below the eyes (Fogel et al., 2006). Like smiling, a cry face becomes more intense when accompanied by eye constriction—hence dubbed Duchenne distress (Mattson et al., 2013).

Cosmetic Botox injections around the eyes and forehead typically mask the intensity of emotions by limiting movements in the top half of the face such as eye crinkling and forehead furrowing. Surgical masks worn to prevent the spread of COVID and other diseases limit access to facial movements of the lower half of the face. Nonetheless, because smiles, cry faces, and other facial expressions typically involve so many muscles moving so many parts of the face, facial expressions are highly redundant and readable even with half the face immobilized or masked. Women's facial expressions are equally readable before and after Botox to the upper face (Dobel et al., 2021), and untrained undergraduates can reliably identify smiling, crying, and interest in infants with severe facial anomalies that limit movements in large parts of the face such as Goldenhar's syndrome, cleft lip and palate, and hemangiomas (Oster, 2003).

Facial expressions in infants, children, and adults are both universal across cultures and highly idiosyncratic among individuals. Expressions are universal in the sense that neonates produce recognizable facial expressions of happiness, distress, and disgust long before they could learn facial movements from observing others (Oster, 2005). For example, in reaction to unfamiliar scents or flavors, neonates wrinkle their noses, raise their upper lips, and furrow their brows, but they respond to familiar smells and tastes with "positive" facial gestures, such as sucking, licking, and mouthing (Mennella et al., 2004). Moreover, people of all ages everywhere smile, laugh, and cry. And finally, people across cultures provide similar interpretations of facial expressions of happiness, distress, anger, disgust, fear, and surprise in photos, and children and adults produce similar facial expressions of those emotions on demand (Ekman & Oster, 1979; LoBue & Thrasher, 2015). Nonetheless, facial expressions are also highly idiosyncratic in the sense that some people's faces are more stoic and some more animated, and small differences in the form or intensity of facial gestures display unique signatures of their bearer's feelings. However, the natural production of facial expressions during everyday interactions is not well documented within or across cultures or contexts.

Eating

Eating is so pervasive in daily life, from newborn to older adult, that people take for granted the movements involved in sucking, chewing, and swallowing until something goes wrong—such as when a baby fails to latch onto the nipple to breastfeed or an older adult has difficulty swallowing due to stroke or dementia.

Viewed from outside, breastfeeding looks simple. But an inside view reveals that the movements are highly complex (Burton et al., 2013). To suck, the lips must create a seal against the nipple (latching on) while the tongue moves up and down cyclically with the jaws; milk flows into the mouth when the downward movement of the tongue creates negative pressure via an intraoral vacuum (Geddes et al., 2012). Bottle-feeding can rely on positive pressure (tongue moves up) because milk is stored in the nipple. To swallow, the tongue moves to transport liquid from the mouth to the throat (Burton et al., 2013). When breathing is added to the mix, all three sets of movements must be coordinated. Although sucking is possible while breathing, swallowing is not. Milk and air share the same passage as they enter the throat, but milk must divert to the esophagus and air to the trachea (windpipe). The trick is for infants to time the various movements so that they do not ingest air (why caregivers "burp" babies after nursing), choke from aspirating milk, or wait too long between breaths (Barlow, 2009; Fucile et al., 2012).

Eating solid food adds more complexity (Wilson et al., 2008). In mature chewing, the tongue moves the bolus (bite of food or swig of liquid) to the appropriate place in the mouth. The jaws move up and down, back and forth, and in rotary motions to create shearing and grinding forces to break up the bolus. The underlying muscle actions are finely attuned to each task constraint (Green et al., 1997). The muscles fire to open the jaws, but due to elastic recoil, the jaws begin to close without additional muscle power. A quick muscle jolt completes the closure without banging the teeth together. The tongue forms the food into a tight ball in preparation to swallow. The lips make a seal, and the tongue pushes the bolus to the throat. All this preparation to swallow is under voluntary muscle control, so people must be alert to plan their actions (Christmas & Rogus-Pulia, 2019). If the bolus does not move into the throat, or diverts to the trachea, they must cough to clear the airway.

Infants can chew even before they have teeth or begin eating solid food. Neonates can move a mushy banana bolus to the middle of their mouth using jaws and tongue (Sheppard & Mysak, 1984). By 12 months of age, infants chew well enough to break down varied types of food (e.g., fresh apples, French fries, crackers, pretzels) and swallow them (Green et al., 1997). But infants' crude strategies for mushing up food are not as distributed, organized, flexible, and automatic as mature adult chewing. Infants rely mostly on side-to-side jaw movements to chew (Simione et al., 2018). It takes years before lip and tongue movements are planned and deliberate and before rotary movements are incorporated into the chewing action. Moreover, infants chew the same way for every kind of food, whereas older children flexibly adapt their jaw movements and chew forces to food consistency and to the emergence of teeth and molars (Simione et al., 2018). Even habitual, automatic actions such as moving the bolus to a consistent, working side of the mouth take years to develop (Wilson et al., 2008).

Older adults may have difficulty chewing food and swallowing due to the loss of teeth and normal aging processes (weakened jaw and tongue muscles for chewing and moving the bolus) or as a byproduct of stroke or progressive neurologic diseases such as dementia or Parkinson's (Christmas & Rogus-Pulia, 2019). One solution is to limit food intake to special foods with just the right viscosity, texture, size, and rigidity (Gallego et al., 2022).

Speaking

Speech sounds—from the universal coos and babbles of infancy to the culturally specific words and speech sounds of children and adults—are the product of motor actions in the face, lips, tongue, and throat. Air is forced through the oral and/or nasal cavities, and the sound is shaped by the position of the jaws, lips, and tongue. Across cultures, speech sounds include 800 different phonemes, including clicks and tones and stops, each produced with slightly different movements (Kuhl, 2015). The motor skills required to produce speech are among the most sophisticated learned by humans (Green & Nip, 2010). After face transplants, adult patients who know all the movements required for speech must still practice for years to retrain their new muscles and tissue to produce intelligible speech sounds (Perry et al., 2022).

Speech movements require only a fraction of the force produced during chewing, but they must be extremely fast and accurate to make the appropriate sounds (Wilson et al., 2008). Adults produce 180 words per minute or 15 sounds per second (Green & Nip, 2010). Although speech and chewing are developmentally distinct behaviors, they share some common developmental features. As with chewing, infants discover functional strategies that get the job done, but the movements are not adult-like. For example, adults use quick simultaneous movements of the jaws and lips to make babbling sounds (baba, mama, dada), but infants rely primarily on their jaws to do the work, and as a consequence they are prone to speech errors and distortions (Green et al., 2000, 2002). Why do children initially use simpler strategies that rely on the jaw? Presumably, the jaw is easier to control. The mandible is a single bone with a network of symmetrical musculature that lifts and drops the jaw. In contrast, the lips and tongue are harder to control because they are highly deformable with layers of muscles. Between 2 and 6 years of age, children get better control over their lips and then incorporate those movements into well-established jaw movements. As a consequence, they can produce a greater range of sounds (Wilson et al., 2008). Like adults who can talk and chew at the same time, infants can vocalize while mouthing objects (Iverson & Fagan, 2004).

Developmental disabilities such as autism and cerebral palsy are often accompanied by motor speech impairments that limit children's ability to produce intelligible speech sounds (Maffei et al., 2023; Mei et al., 2014). Likewise, aging is associated with deficits in speech production. Older adults talk slower and make more articulation errors, especially for vowel sounds, due to slower, more variable movements of the tongue (Hermes et al., 2018).

Summary

Researchers often forget that emoting, eating, and speaking are part of motor development, but these actions require facial movements and are critical to function in a social world. Complex facial movements enter the repertoire during fetal development, and the variety and complexity of facial actions continue to expand across the lifespan. Like other action systems, facial actions are highly redundant, and various movement strategies can accomplish the same end goal. Also like other action systems, the same facial actions for emoting, eating, and vocalizing can be categorically universal, although the production and end result are idiosyncratic to particular individuals, developmental levels, and sociocultural groups.

Manual Actions: Interactions With Objects

Manual actions differ from other types of movements in two important ways. First, of course, manual actions involve the arms and hands. But second, manual actions typically involve physical interactions with something else—an inanimate object or surface or an animate body (one's own or another's; Figure 6.1E). In terms of function, the interactive nature of manual actions means that these movements are geared for exploring or enacting change on the target. In terms of motor control, the person must first get hands to the target. This transport phase requires perception (von Hofsten & Rosander, 2018). For external things like a toy or a coffee cup, typically vision locates the target. For one's own body, the perceptual information can be visual (like buttoning a shirt), proprioceptive (like moving the hand to the lap), and tactile (like scratching an itch). After arriving at the target, many manual actions also require small movements of the arms, fingers, thumb, and palm to grasp and manipulate the target. For all manual actions, postural control supports getting the hands (and eyes) to the right place.

Self-Touch

Like fetuses, young infants spontaneously touch every reachable part of their body and the surroundings at a rate of about 10 touches per minute—head, face, trunk, arms, and the ground around the upper half of their body if they are lying supine (DiMercurio et al., 2018). Older infants, like adults, alter their posture to touch legs and feet on the lower half of the body (Thomas et al., 2015).

To plan a reach to a tactile target on the body, say to remove an annoying strand of hair from your forehead, a bug tickling your arm, or a small vibrating button placed by an experimenter, requires the tactile sensation on the skin to be located on a body map relative to the reaching hand. Watching a person expertly apply mascara sans mirror on a jerking subway car is a revelation in the skilled performance of self-touch.

Infants reach to a vibrating button on their mouth at younger ages than they reach to one on their chin, forehead, ear, or temple, although all locations are just as easy to reach (Chinn et al., 2021; Leed et al., 2019). They reach to a vibrating target on the palm at younger ages than they reach to one on other parts of the arm, despite all target locations being visible. They know to reach with their closer arm to targets on the head but to reach across their body to targets on the other arm. Likely, such biases are the result of months of practice beginning in utero. With increasing age, infants move their target arm toward their reaching arm to assist in the removal of the target—a feat of bimanual coordination with a spatial reference frame that shifts as the target arm moves toward the reaching arm (Chinn, Hoffman, et al., 2019). Infant self-touch—whether spontaneous or to a vibrating button—develops from hands fisted to a palmar grasp, just as it does for reaching to a target external to the body (Chinn, Noonan, et al., 2019; Thomas et al., 2015).

Self-touch, like every action, is embedded in a perception–action loop. Touches to the body provide information about the limb posture in space, the part of the limb contacting the body, and the body area being touched—all concurrent in time (DiMercurio et al., 2018). Often, the multimodal proprioceptive and haptic information is linked with visual information—as while watching one hand move to touch the other hand. When visual information about touching invisible body parts like the forehead is provided via training with vibrating buttons and a mirror, infants show earlier success at touching a smudge of rouge on their forehead that they can only see in a mirror—the mirror-mark test of self-concept (Chinn, Noonan, et al., 2024). In short, a primary way to learn about the body (and to acquire self-concept) is by touching the body.

Transporting Hand to Target

Infants' spontaneous arm flails and self-touch behaviors set the stage for reaching to targets at a distance from the body (for reviews, see Corbetta, 2021; Corbetta et al., 2018). The sight of an attractive object provides an important impetus to reach. Sounding objects help motivate blind children to reach (Ihsen et al., 2010), but blind children are extremely delayed nonetheless in acquiring manual actions (Brambring, 2007).

Neonates stare attentively at enticing objects, but they can get only their eyes, not their hands, on the target. Over the ensuing weeks, infants become aroused at the sight of objects and flap their arms haphazardly. Their first object contacts at 3 to 5 months of age (a sort of swat, sans grasp) have zigzag trajectories, with multiple changes in course direction and speed bursts and reaching paths up to four times longer than the straight-line distance to the object (Konczak et al., 1995; von Hofsten, 1991). Adult reaching paths, in contrast, are approximately the distance between hand and target, with one big acceleration toward the target and a deceleration as the hand prepares to grasp (Konczak et al., 1995). Infants learn from their first—likely serendipitous—contacts with objects to control their reach trajectory by mapping the feel of their arm movements (highly practiced from spontaneous arm movements and self-touch) with the sight of the distant target (Williams & Corbetta, 2016). Consequently, infant reaches become straighter and more direct (Berthier & Keen, 2006; Corbetta, 2021; von Hofsten & Rosander, 2018).

However, because reaching depends on posture, learning to reach has different developmental timelines for prone, supine, and sitting postures (Carvalho et al., 2008; Spencer et al., 2000). While prone or tripod sitting, one or both arms are engaged in supporting the body (Soska & Adolph, 2014). While supine, infants must work hard to hold their arms overhead. While sitting with arms free, pre-sitters and new sitters reach earlier and better when their sitting posture is supported than when they must control posture independently (Rachwani et al., 2013). With increased postural control, the reaching space expands from in front of the moving arm to the midline and to the far side of the body (Chinn, Noonan, et al., 2019).

Although reaching is a single action, often the plan to reach must incorporate the next action in the sequence. For example, sometimes transport involves bringing an object in hand to a particular location, such as placing a coffee cup on the table, putting a block on a tower, or tossing the block into a bin. Adults—and 10- to 21-month-old infants—plan their initial reaches differently depending on what they intend to do next (Keen, 2011). The reach is slower with a longer deceleration if the adult plans to place a cup on the table rather than merely hold it or if the toddler plans to put the block atop a tower rather than throw it in a bin.

Sometimes the hand—or an object in hand—must be oriented appropriately during transport, such as fitting the hand or an envelope through a mail slot. Infants and young children often fail to orient their hands, Duplo bricks, blocks, and so on before arriving at the destination (Ishak et al., 2014; Kaplan et al., 2022; Ossmy et al., 2020). So, the adjustments are trial and error, after contacting the target. Children do not accurately orient and shape their hand to fit it through an aperture until 7 years of age (Ishak et al., 2014). Pre-orienting the object requires looks to both the grasped object and the target opening, but unlike adults, young children do not look at the aperture soon enough to pre-orient the object during transport (Ossmy et al., 2020). It's a failure of planning to plan.

During childhood and adolescence, transporting the arms and hands to targets continues to improve. In addition to reaching, children learn to hit, catch, and throw balls and perform other manual sport skills, depending on their families' beliefs, practices, and cultural milieu (Jarvis et al., 2020). However, despite physical education curricula, many school children never master basic manual sport skills (Duncan et al., 2020).

Grasping, Object Manipulation, and Tool Use

Getting the hand to a target is often only the first step. Next, the fingers and hands come into play. Grasping must be geared to object size, shape, and orientation. Young infants' hands are fisted at object contact. At older ages, infants' hands are open, but the fingers close only after contact. Finally, infants learn to use visual information about the object to adjust their hand orientation and distance between fingers and thumb prior to contact (Fagard & Marks, 2000; Schum et al., 2011; von Hofsten & Rosander, 2018). Even for tiny objects, power palmar grips, where all fingers wrap around the object, developmentally precede precision pincer grips, where the object is grasped between thumb and forefinger (Barrett et al., 2008). Older infants know to use one hand to grasp small objects and two hands to grasp large ones, and they adjust the space between the two hands to object size (Fagard & Marks, 2000; van Wermeskerken et al., 2011). By 3 years of age, scaling is so fine-tuned that children switch from one- to two-handed grasps when the object is larger than the distance between fingers and thumb on one hand (Huang et al., 2013).

Like reaching, grasping an object must also take the next action into account. The human hand can easily grasp an object with their palm down or up, but from infant to adult, overhand power grips (palm down) are more habitual. Younger infants use an overhand power grip to grasp a spoon, hammer, hairbrush, or any handled tool—regardless of the handle direction (for reviews, see Adolph & Robinson, 2015; Keen, 2011). So, if the handle of a spoon points away from the reaching hand, an overhand grip puts the pinky finger near the bowl of the spoon, making it impossible to bring food to the mouth, or the infants' palm is on the bowl of the spoon, resulting in a handful of applesauce. At older ages, infants swap hands to maintain an overhand grip while planning for the subsequent action. It is not until 8 to 12 years of age that children show adult-like planning for the subsequent action by consistently using an underhand grip with their preferred reaching hand to grasp the handle of a spoon or hammer so that their hand is in the optimal position for the next action in the sequence (Comalli et al., 2016; Keen et al., 2014; Ossmy et al., 2022).

Spoons are surprisingly difficult tools to manage, but chopsticks—used by billions of people around the world—are even more challenging. One chopstick must be held stationary while the remaining fingers lift the other stick up to grasp food and then down to pinch the food with sufficient force to transport it. Children must learn to differentiate the roles of the fingers for stabilization versus grasp, and small differences in the shape of the handles (round, triangular, square, octagonal) affect children's skill and age at mastery (Yokubo et al., 2021).

Grasping a pen or pencil to write is also extremely challenging. Handwriting must produce particular traces on the paper, but the movements involved can be wildly variable across people and contexts. The developmental path to legible handwriting is idiosyncratic across children, and as the marks on paper increasingly conform to cultural norms, handwriting also becomes faster, smoother, more automatized, and more personalized—such that each person's handwriting is simultaneously universal and unique (Nonaka, 2017; Palmis et al., 2017).

Some aspects of tool use have their origins in infants' first spontaneous behaviors (Lockman, 2000). Hand-to-mouth behaviors set the stage for bringing food to the mouth with a spoon or chopsticks. Arm flaps and banging set the stage for hammering. And sliding the hand back and forth across a surface sets the stage for handwriting and drawing. But many designed uses of everyday objects must be discovered before perfecting the perceptual-motor skills to implement them (Kaplan et al., 2022; Rachwani et al., 2020, 2021). Thus, children easily recognize that a container or zipper pouch must be opened or Duplo bricks must be put together. But it takes many more weeks or months to discover that the container lid must be twisted, zipper tab must be pulled, and Duplos must be interlocked. And there is another substantial lag between knowing the requisite motor action and acquiring the subtle perceptual-motor skills to implement it—such as stabilizing the container with one hand while twisting the lid continuously to the left with the other.

At the other end of the age spectrum, elderly adults are stymied by "child-proof" containers, zipper tabs, and so on because they lack the grip strength, dexterity, and perceptual sensitivity to implement the necessary actions. Imagine learning to apply eye liner in later life, that is, with a shaky hand and without wearing the glasses you need to focus on nearby objects like your face in a mirror.

"Manual" Actions With Feet

We normally think of the human hand as the most dexterous manipulator on the body. But humans born without hands can learn to use their feet for complex manual actions like brushing their teeth, peeling a banana, lighting a cigarette, and writing or typing (Blumberg, 2009). Typically developing babies can use their legs for reaching and their toes for grasping (Brainard, 1927; Galloway & Thelen, 2004). And children everywhere learn feet-based object interaction skills like kicking a stone, juggling a hacky sack, or dribbling a soccer ball (Newell, 2020). Likewise, people and nonhuman animals born without legs can learn to walk on their hands (Blumberg, 2009). Action systems are more functional than anatomical.

Summary

Object interactions expand people's motor, perceptual, and cognitive abilities. Manual actions provide multimodal feedback about the target object and what the body is doing with it. Manual actions have their roots in spontaneous fetal and infant activity such that seemingly cognitive aspects of development—tool use, self-concept, and so on—may be sensorimotor, at least in part. Objects are so pervasive in activities of daily living that people continue to learn new uses of objects and new ways of interacting with objects across the lifespan.

Locomotion: Going Places

Locomotion functions to move the whole body from one location to another (Figure 6.1F). Whereas stationary postures like sitting and standing facilitate manual actions with objects, the dynamic postures involved in locomotion are geared toward exploring and negotiating ground surfaces and places and toward situating the body for subsequent looking and manual actions (E. Gibson, 1988).

Precursors to Walking

Months before they can stand upright or walk independently, most infants find transient solutions for independent mobility (for review, see Adolph & Hoch, 2019). Many babies find creative, idiosyncratic solutions that minimize balance constraints by keeping large parts of the body on the ground. They log roll with arms and legs outstretched, belly crawl dragging their stomach on the ground, inchworm by flopping on and off their bellies, snowplow on the legs and head, crab crawl on their backs, bum shuffle in a sitting posture, or hitch in combinations of sitting and crawling. With the belly or buttocks on the ground, nearly any combination of limb movements propels infants forward. Indeed, even neonates can squirm around with their bellies resting on a wheeled skateboard, although their limb movements are uncoordinated and they cannot control their direction or speed (Forma et al., 2019).

Most infants eventually take crawling steps on hands and knees or hands and feet. After babies can crawl several feet (a meter or two) on hands and knees, they typically settle into a trot-like gait pattern, where diagonal limbs move in close synchrony (Adolph et al., 1998; Patrick et al., 2012). However, hands–knees crawling is not an obligatory milestone enroute to walking (for reviews, see Adolph & Hoch, 2019; Adolph et al., 2010; Adolph & Robinson, 2015). In some cultures and time periods, sizeable proportions of infants do not crawl before they walk. Indeed, the U.S. Centers for Disease Control and Prevention eliminated crawling as a diagnostic milestone due to the diversity of non-upright solutions, variability in coordination patterns, variability in ages when infants begin crawling, cultural and historical differences in caregivers' value of crawling, and evidence that some typically developing infants crawl after—not before—they can move upright (Kretch et al., 2022).

After infancy, children and adults typically crawl only to retrieve something under the table or negotiate a treacherous hiking path. But when asked to crawl, 11- to 12-year-old children crawl faster than infants and young adults, and children crawl in ways rarely seen in infants or young adults, like "bunny-hopping" from feet to hands (Cole et al., 2019). Moreover, in contrast to infants, children can crawl with only one limb on the ground or even "fly" through the air with all four limbs off the ground. In a few instances in isolated communities, adults choose to crawl as their habitual form of locomotion—despite their ability to walk (Shapiro et al., 2014).

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When infants have sufficient strength to hold part of their body weight on one leg, they cruise sideways along furniture or hold the wall for support (Adolph et al., 2011). Like crawling, hitching, and so on, cruising also allows for a variety of gait patterns, with each arm and leg moving one at a time or in near-synchronous combinations (Ossmy & Adolph, 2020). For several weeks or months, pre-walking infants can both crawl and cruise (Adolph et al., 2011), so they cruise when external supports are available because the upright posture gives them a better view of the room (Kretch et al., 2014), and they crawl when they need to travel over open ground.

Cruisers can also "walk" with support by pushing a cart or holding caregivers' hands. As infants' own leg strength and balance gradually replace the support provided by furniture and adults, infants exert less force on their hands, bear more weight on their legs, and keep their bodies more vertical (Haehl et al., 2000). Eventually, infants require only one hand for cruising and supported walking, and at some point, the furniture or caregiver's finger provides more social reassurance than physical balance. Indeed, some babies take their first independent steps with one hand in the air, as if they were holding a caregiver's finger. Thus, a handrail, parents' hand, and other such supports have different functional meanings at different points in development. For cruisers, external supports are obligatory for upright locomotion. For walkers, external supports are supplemental and enable walking over treacherous ground.

Walking and Running

No one knows why infants take their first walking steps. Given that infants are already skilled crawlers and cruisers, why learn to walk? Likely, the immediate, tangible benefits of walking outweigh the initial costs (Adolph & Tamis-LeMonda, 2014). While walking, infants can see more, go more, and interact more compared with crawling. Novice walkers see more of the surroundings than experienced crawlers because walkers' faces point out at the room rather than down at the floor (Kretch et al., 2014). Novice walkers cover more distance and move faster than experienced crawlers because upright posture is more comfortable and consumes less energy (Adolph et al., 2012; Thurman & Corbetta, 2017). Because they can move farther and with arms free, novice walkers spend more time engaging with objects far afield, and they carry objects and share them with caregivers (Heiman et al., 2019; Karasik et al., 2011). Caregivers, in turn, provide new forms of verbal input to walkers (West et al., 2023). Finally, social pressures motivate infants to walk. Caregivers everywhere encourage infants to walk independently, and infants across cultures and time periods observe others walking.

Novice walkers fall, on average, 32 times per hour (Adolph et al., 2012). Why doesn't falling dissuade infants from learning to walk? When the fall rate is normalized by how much babies move, novice walkers do not fall more than experienced crawlers (Adolph et al., 2012). Moreover, most infant falls are trivial. Babies rarely fuss, caregivers rarely show concern, and falling does not deter infants from walking or from interacting with the objects or surfaces that precipitated the fall (Han & Adolph, 2021). In fact, infants are "built" to fall. Babies are low to the ground and move slowly, so the impact forces are 18 times less than if infants were adult sized and walked at adult speeds. Formal modeling with simulated robots shows that a low penalty for falling promotes learning to walk (Ossmy et al., 2024). A system that can safely ignore frequent errors can push its limits and practice to the point of mastery. In contrast to infants, falling is dire for elderly adults. For elders, standing and walking falls frequently lead to serious injury (Stevens et al., 2008), and fear of falling constrains their daily activities (Chamberlin et al., 2005).

While learning to walk, infants accumulate immense amounts of self-generated, time-distributed, variable, error-filled practice (for reviews, see Adolph & Hoch, 2019; Adolph & Robinson, 2015). On average, toddlers take 2,400 steps and travel 2,300 feet/700 meters (the length of almost eight American football fields) per hour (Adolph et al., 2012). They take steps in every direction, make frequent starts and stops, walk curved and windy paths, and visit most of the available area (Hoch et al., 2019; Hospodar et al., 2021; Lee et al., 2018). Moreover, every variation in terrain, footwear, and clothing adds variability to infants' practice regimen. Even something as seemingly mundane as a diaper affects infant walking and falling (Cole et al., 2012). Formal modeling with simulated robots shows that variability in infant walking leads to better, more functional walking skill (Ossmy et al., 2018).

Indeed, infants' everyday walking experience leads to rapid improvements in walking skill (for reviews, see Adolph & Hoch, 2019; Adolph & Robinson, 2015). New walkers take short, jerky steps (due to poor balance on one leg), with their feet so wide apart that step width may be larger than step length. Arms are typically flexed at the elbow in a frozen jazz-hands position. After 4 to 6 months, steps are longer, feet closer together laterally, and arms swing in unison with the opposite leg. Although infants cannot know that practice will improve walking skill and confer long-term benefits, they behave as though they do. Most of infants' walking bouts do not end at a recognizable person, place, or thing—meaning they move with no immediate, external goal (Cole et al., 2016; Hoch et al., 2019, 2020).

While walking, one foot is always on the ground. But running has periods with both feet in the air. Infants rarely run; instead, they "speed walk" to avoid a flight phase. After infancy, children and adults walk and run at various speeds. But walking and running gaits differ between cultures, between women and men, between athletes and couch potatoes, and so on (Devine, 1985). For example, in cultures where long-distance running is part of everyday activity (for travel, hunting, work, carrying messages, sport, spiritual practices, etc.) and people run barefoot, they land on their forefoot or midfoot with their moving leg nearly vertical, not on their heel with their moving leg outstretched diagonal to the ground (Wallace et al., 2022). Notably, the modern running shoe is designed to land on the heel with the leg outstretched, and that is how most Western athletes run.

Nonetheless, bipedal locomotion is universal among people everywhere throughout history. Why? One explanation is that bipedal locomotion was an evolutionary adaptation for traveling long distances at relatively high speeds while carrying burdens, particularly for persistence hunting before long-range weapons emerged (Devine, 1985; Liebenberg, 2006; Lieberman et al., 2020). Persistence hunters follow an animal for hours over grueling terrain, driving the animal into hyperthermia or exhaustion so that it can be killed safely at close range. In cultures where load carriage is common, people learn to carry prodigious loads—more than their body weight—without incurring increased energetic costs (for review, see Adolph & Robinson, 2015).

Navigation Over Varied Terrain

At the same time that infants learn to walk, they learn about the environment and what they can do in it. Functional locomotion involves selecting the appropriate action, modifying ongoing movements, and discovering alternative strategies—what J. Gibson (1979) called perceiving affordances for action.

Whereas older children and adults perceive affordances for locomotion, newly crawling and walking infants do not (Adolph, 1997). They plunge straight over the edge of an impossibly high drop-off, steep slope, narrow bridge, or wide gap (for reviews, see Adolph & Berger, 2006; Adolph & Hoch, 2019; Adolph et al., 2021; Adolph & Robinson, 2015). Over weeks of everyday crawling and walking experience, the perception of affordances gradually improves until infants achieve adult-like levels of accuracy. Infants can even update their assessments to account for novel changes in their bodies such as lead-weighted shoulder packs and slippery-soled shoes while walking down slopes. Although infants' experience outside the laboratory does not include high drop-offs, steep slopes, narrow bridges, heavy backpacks, and so on, likely, the demands of coping with the variability inherent in their own bodies and everyday environments teach them to perceive affordances in novel situations.

Typically, adult walking is visually guided (J. Gibson, 1979; Kretch & Adolph, 2017; Matthis et al., 2018)—from a long distance (e.g., spotting an upcoming obstacle), a few steps ahead (e.g., while navigating irregular, rocky terrain), and in the course of a single step (e.g., to avoid landing on a wet stone while the foot is in the air). Experienced walking infants likewise use visual information from a distance to spot upcoming obstacles and guide their steps, but they also stop at the edge of an obstacle to explore it with hands and feet (poke a foot into the abyss, rock their feet at the brink of a slope, etc.) and to test out alternative strategies for traversal (for reviews, see Adolph & Hoch, 2019; Adolph & Robinson, 2015). Infants also use social information from caregivers' words, tone of voice, facial expressions, manual gestures, and body position to decide whether an obstacle is passable. Adult runners use visual information from a distance to avoid large obstacles like a high drop-off or a barrier in the path, but they rely on the bendy compliance of their leg joints to cope with undulating, uneven terrain (Dhawale & Venkadesan, 2023). Elderly adults sometimes underestimate their abilities or refuse to attempt passage over potentially risky ground such as narrow ledges due to fear of falling (Comalli et al., 2013).

The world in three dimensions is a natural playground for infants and children to climb up and down—slopes, trees, fences, ladders, stairs, crib rails, toy boxes, overturned buckets, and furniture. In general, going up is more energetically costly but easier to control than going down. Upward motions are tiring to hoist the body against gravity. However, gravity slows forward momentum and provides time to place the limbs into appropriate positions. Upward climbing motions exploit leg strength, relieving crawling infants' weaker, spindly arms from their usual contribution to support. In fact, infants who cannot lift their bellies off the floor while horizontal can push themselves onto their knees or feet while climbing up slopes or stairs. The supporting arm or leg is typically extended so that muscles contract to produce force. The moving limb traces a smaller arc than it does during locomotion on flat ground, and it contacts the slope, riser, or rung while still in a flexed position. In the event of a fall, the hands are well positioned to protect the face.

In contrast, going down slopes, stairs, and ladders is less tiring but more difficult to control. Moving the body in the direction of gravity is energetically efficient, but forward momentum can make downward motions spin out of control. While crawling down slopes, infants must support more body weight on their weak arms than they would on flat ground, exacerbating the problem of keeping balance. Likewise, novice walkers may lack sufficient strength to walk down slopes and stairs because to bear weight on the bent support leg, their muscles must lengthen rather than contract, requiring more strength to produce force.

Infants' success at climbing reflects the different biomechanics of going up versus going down. For example, after an intense regimen of daily practice, one infant climbed up a 70° slope using his hands to grip and toes to propel, but the steepest slope he crawled down was 40° (McGraw, 1935). After daily practice on stairs, one infant clambered up a staircase on hands and knees in 26 seconds whereas another sprinted up in 10 seconds, but neither infant could crawl down independently (Gesell & Thompson, 1929). Likewise, without special training, infants can crawl and walk up steeper slopes than down (Adolph, 1997). Indeed, in cultures where climbing is required to harvest food or to hunt, children and adults show prodigious climbing skills to scale tall trees and cliffs and to move from one tree to another in the canopy (Venkataraman et al., 2012). The human foot, adapted for bipedal locomotion, does not preclude climbing.

Travel may broaden the mind (Campos et al., 2000), but reciprocally, the mind can enrich one's travels. As with manual actions, effective strategies for coping with challenging locomotor tasks often involve higher-level problem-solving skills. For example, infants, like adults, can recognize external supports to solve locomotor problems. A 2- to 3-year-old can stack boxes from large to small to climb to a lure hung from the ceiling (McGraw, 1935). Babies recognize the utility of a handrail to augment their balance on narrow bridges, but only when the handrail is within reach of the bridge (Berger et al., 2010). When faced with descent of a steep slope or high drop-off, experienced crawlers and walkers can correctly perceive that crawling or walking are impossible, but they do not have a ready-made solution to get down (Adolph, 1997). Eventually, infants demonstrate means–ends exploration by testing various strategies for descent—sliding headfirst like Superman, scooting down in a sitting position, or backing feet first. Backing is the latest to appear because it is the most cognitively demanding. Infants must put themselves into a prone position, execute a detour by pivoting 180° away from goal, and finally move backward toward the goal while facing away from the direction of travel. Locomotion with reversed visual guidance is difficult (imagine walking backward without peering over your shoulder or driving in reverse without looking in the rearview mirror). In addition, unless a caregiver stands at the bottom shouting encouragement, infants must represent the goal destination in memory. Thus, whole-body problem solving can highlight external support as tools for locomotion, and means–ends exploration can facilitate the discovery of alternative locomotor strategies.

Summary

From infants to elderly people, everyone wants to go places. Deciding how to get there requires perception of affordances and sometimes higher-level cognition to figure out a means to achieve the goal. Locomotion is endlessly creative. Long before and long after they can walk, infants discover new solutions for mobility and for navigating obstacles. Like other basic motor skills, walking is overdetermined—many factors conspire to inspire infants to walk. Also like other basic motor skills, everyday experience with walking (and likewise, crawling, running, and so on), leads to improvements in proficiency and in perception of affordances. Cultural differences in people's experiences lead to different forms of locomotion with different ages at onset and differences in performance.

Conclusions

This chapter focused on spontaneous movements and five functional action systems (Figure 6.1): posture to support other action systems, looking to guide action, facial actions to facilitate social interaction, manual actions to facilitate object interaction, and locomotion to access the environment. Several themes across these sections illustrate the importance of motor development for developmental science in terms of behavior, psychophysiology, context and culture, and change processes.

(1) *The study of motor development is really the study of behavioral development*. Behavior is ubiquitous. People are always moving—while they sleep and during every waking activity. Movements begin in fetal development, and behaviors continue to grow and change throughout the lifespan.
(2) *All movements are embodied*. Across lifespan development, the biomechanical constraints of the body and emerging skills constrain or facilitate movements. However, the action systems that underlie central behavioral functions (e.g., interactions with people and objects, locomotion) are only loosely related to anatomy. People can communicate with their hands, reach with their feet, and locomote with their arms.
(3) *The development of action systems is overdetermined*. Many redundant factors contribute to ensure function across individuals despite differences in their physical and sociocultural environments. Equifinality—different paths to the same outcome—is a staple of motor development. Reciprocally, "universal" behaviors like facial expressions, talking, sitting, and walking can be accomplished in different ways depending on the individual and the larger environmental context. Multifinality—different outcomes stemming from similar starting points—is also a staple of motor development.
(4) *Action is always linked with perception*. Movements give rise to perceptual feedback about what just happened, perception guides what movements to do next, and movements are required to generate perceptual information. Even looking involves movements of the eyes, head, and trunk; postural control to support those movements; and locomotion and manual actions to put the body or the object in the right place for looking.
(5) *Behavior is always contextualized in a physical and sociocultural environment*. Environments constrain movements but also provide opportunities to move and thereby to explore, learn, and do. To cope with and exploit the constraints and opportunities provided by the body and environment, actions are endlessly creative.
(6) *Experience is the primary driver of improvements in motor behavior*. People accumulate hundreds to thousands of experiences per day for the basic actions involved in maintaining and transitioning among postures; looking around; using the face to emote, eat, and vocalize; acting on objects; and going places—immense amounts of time-distributed, variable, error-filled practice. Errors are most frequent during infancy, when the foundation for action systems is established, but infancy is also the time period that is most forgiving of movement errors.
(7) *Qualitative changes in motor development are best considered cascades of events rather than obligatory stages*. Many motor behaviors undergo radical transformations. Fetal and newborn leg kicks transform into the leg movements involved in locomotion and sport. Fetal hand-to-mouth behaviors transform into bringing food to the mouth with a spoon. Moreover, motor behaviors cascade into psychophysiological functions far afield from the original movements. Locomotion and sport influence physical fitness and peer interaction. Self-touch in the fetus and infant lays the groundwork for learning about the body and acquiring a self-concept.
(8) *Motor development provides a window into general processes of change*. Given the accessibility of motor behavior at every time scale and the scope of behavioral development

across the lifespan, developmental scientists would do well to leverage the power of motor behavior.

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