Motor Development in Context

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Summary

The study of motor development has traditionally focused on the timing and sequence of the acquisition of motor skills, such as sitting, crawling, or walking, over the first years of life. Because motor skills are directly observable, motor development serves as a useful exemplar for general principles of development. Current frameworks emphasize motor development in and as a context, such as how change in motor skill interacts with simultaneous change in other developmental domains, how the acquisition of new motor skills creates new opportunities for learning, and how the context in which motor development occurs shapes the course of development. For example, the onset of new motor skills changes the allocation of attentional resources, the quality of infants' sleep, and available perceptual information. Reciprocally, contexts such as culturally specific parenting practices and individual differences in everyday experiences impact the timing and trajectory of new motor skills.

Keywords: motor development, infancy, embodied cognition, culture, perception–action, sleep, individual differences, sitting, crawling, walking

Subjects: Developmental Psychology

Introduction

Traditionally, articles and chapters on motor development have emphasized developmental norms—the age at which infants typically achieve a given motor skill, such as sitting, crawling, or walking, and in what order those skills are acquired (e.g., Anderson et al., 2017; Clark, 2005). This framework has been the standard reference, such as in parenting advice books and pediatricians' growth charts. However, there are (at least) two problems with this approach. First, these norms stem from 100-year-old research on samples that are not by and large generalizable. Arnold Gesell's original work from the 1920s and 1930s (Gesell, 1928, 1934) documenting the minutiae of skill acquisition, such as the 9 "stages" of learning to reach or the more than 20 "stages" of learning to crawl, was based on an exclusionary sample of infants (Gesell, 1929; Weizmann, 2010). Infants of British or German ancestry living in two-parent homes were selected to participate. This means that the motor milestone guidelines used to chart development are not representative and referring to them as "norms" is a generalization without context. As such, researchers have challenged the long-held belief that motor milestone acquisition occurs in an orderly sequence (e.g., Vereijken & Adolph, 1999). The second problem with an approach that emphasizes developmental norms is that it focuses on group averages and glosses over the remarkable variability that characterizes development (Hadders-Algra, 2002; Siegler, 2002). In fact, individual differences in timing and order of skill acquisition are a hallmark of motor development (e.g., Atun-Einy et al., 2012; Berger et al., 2007; Martorell et al., 2006). Even Gesell, the father of developmental norms, described infants' unique trajectories, while focusing on "normative psychology" (Gesell, 1928, p. 125). Finally, the focus on norms applies a prescriptive nature on motor skill acquisition rather than describing developmental change and explaining the enormous variability in what, when, and how motor skills are acquired. The first section of this article describes research that emphasizes how changes in motor skill shape and are shaped by changes in other developmental domains. The second section highlights the individual differences in infants' experiences that shape the trajectory of motor development. Together, they highlight current frameworks for thinking about motor development in and as a context.

Interaction Between Domains

Studying different areas of development, such as motor, language, cognition, and so forth, in isolation can be expedient, but that approach does not reflect the reality that developmental change is occurring simultaneously across multiple domains over the life span (Berger et al., 2018). In fact, there is an inextricable link between developmental domains whereby change in one domain can directly impact change in another. Moreover, the timescale of that change can vary. Whereas previous work has demonstrated that motor learning can happen on both short- and long-term timescales (Newell et al., 2001), the reciprocal relationship between developmental domains that shapes their respective trajectories also happens on multiple timescales. This article illustrates these ideas using motor development as an exemplar.

Motor Development "In the Moment"

Embodied Cognition

On an embodied cognition account, cognition develops from having a body that interacts on and with the world and whose motor abilities constrain possibilities for learning (Thelen, 2000). More specifically, embodied executive functioning (EF) describes executive control and planning of actions as stemming from prospective control of action (Gottwald et al., 2016). For example, infants were slower to reach for a ball when they planned to fit it into a hole than when they planned to throw it (Claxton et al., 2003). The kind of prospective planning involved in executing a reach was also related to 18-month-old infants' ability to inhibit and to their working memory, classic indices of EF (Gottwald et al., 2016).

With physical growth and acquisition of new motor skills occurring across the first year, learning and cognitive skill change accordingly (Needham & Libertus, 2011). Effortful or demanding body movements, such as threats to balance or mastering a new skill, impose demands on infants' attention, suggesting an embodied cognitive load (see Berger et al., 2018, for a review). As motor skills are automatized, less attention is required to execute them (Berger et al., 2018). For example, using video magnification software (Wu et al., 2012) to amplify sitting infants' normally "invisible" real-time trunk and pelvic movements made subtle postural adjustments visible on video (Berger et al., 2019). This unconventional motion analysis approach shed light onto the mechanism underlying the trade-off between postural control and attention: Infants who were able to minimize small movements of the trunk/pelvis during focused attention (but not during non-focused attention) freed up attention to allocate to object exploration. Similarly, unskilled sitters took longer to visually process objects than experienced sitters, and focused attention improved as sitting became automatic, possibly due to greater postural control freeing up attentional resources (Harbourne et al., 2014; Surkar et al., 2015).

As new sitters learned to combine sitting and reaching so they could obtain objects, errors of balance, such as falling over, increased. Infants attended to reaching but could not also attend to maintaining postural control while sitting (Harbourne et al., 2013). In fact, infants persisted in reaching while falling and did not find falling a deterrent to subsequent reaching (Harbourne et al., 2013). Similarly, falling does not deter new walkers from continuing to walk (Han & Adolph, 2021). Perhaps persistence in the face of errors is the mechanism by which novices acquire sufficient experience to automatize their motor skill and free up attention for other learning.

A behavioral pattern associated with embodied cognitive load is cognition–action trade-offs. In day-to-day life, this may manifest as having to pause a conversation with a passenger in the car while driving an unfamiliar route. Reducing the load by asking for silence allows the driver to allocate more attention to driving (Berger et al., 2018). In infancy, this pattern manifests when attention is allocated to mastering a new motor skill at the expense of higher level cognitive demands. For example, over the transition to crawling and walking, novice crawlers and walkers had more difficulty inhibiting a prepotent behavior than age-matched experienced crawlers and walkers (Berger, 2010). Once crawling and walking were automatized, infants more efficiently solved the locomotor problem of navigating an obstacle (Berger, 2010; Berger & Scher, 2017). As illustrated in figure 1A, experienced walkers were better able to come up with alternative locomotor solutions, whereas newly walking infants struggled to inhibit their preferred posture of walking for a safer, more stable solution requiring a switch to crawling or scooting (Berger et al., 2015). In addition to problem solving, embodied cognitive load also has implications for strategy use. Even after new walkers switched to crawling to navigate a tunnel or to scooting on their bottoms to descend a staircase, they often stood up midway through/down, even though it meant bumping their heads (see video 1) on the top of the tunnel or needing to be rescued when they lose balance on stairs (Berger et al., 2015; Horger & Berger, 2019).

Video playback is not supported in this format.

Video 1. New walker solving the problem of navigating a tunnel. Difficulty inhibiting walking in favor of the alternative strategy of crawling leads to bumping her head on the tunnel ceiling.

Source: Video courtesy of Dr. Sarah Berger, Child Development Lab.

Speech

The interaction between speech production and motor control is another example of embodied cognitive load. Speech and language production rely on purposeful and coordinated movements of the mouth (Iuzzini-Seigel et al., 2015). Certainly, improvements in speech motor control contribute to more mature speech, such as an increased rate or wider range of produced phonemes (Green et al., 2000; Nip & Green, 2013). However, more than just biomechanics determine speech production. Speech involving semantics or communicative intent also requires cognitive processing (Nip et al., 2009). Increasing language demands, such as generating a sentence rather than imitating one, prompted decreasing efficiency in the motor control of speech production (Nip & Green, 2013; Saletta et al., 2018).

A longitudinal, naturalistic observation of the relation between motor and language development revealed changes in that relationship as a function of motor expertise, including behavioral trade-offs (Berger et al., 2017). Infants were less likely to simultaneously vocalize while crawling or pulling-to-stand within the first couple of weeks of motor skill onset than after they had attained several weeks of crawling/pulling-to-stand experience (figure 1B). Moreover, the mean duration of crawling bouts when infants vocalized were shorter than bouts when they did not, despite having more opportunity to vocalize during long bouts. Language skills “made room” for motor skills due to the increased attentional load associated with skill acquisition. Thus, in both experimental and naturalistic contexts, with increased motor expertise, more attentional resources become available for inhibition of prepotent responses, strategy selection and maintenance, and vocalization.

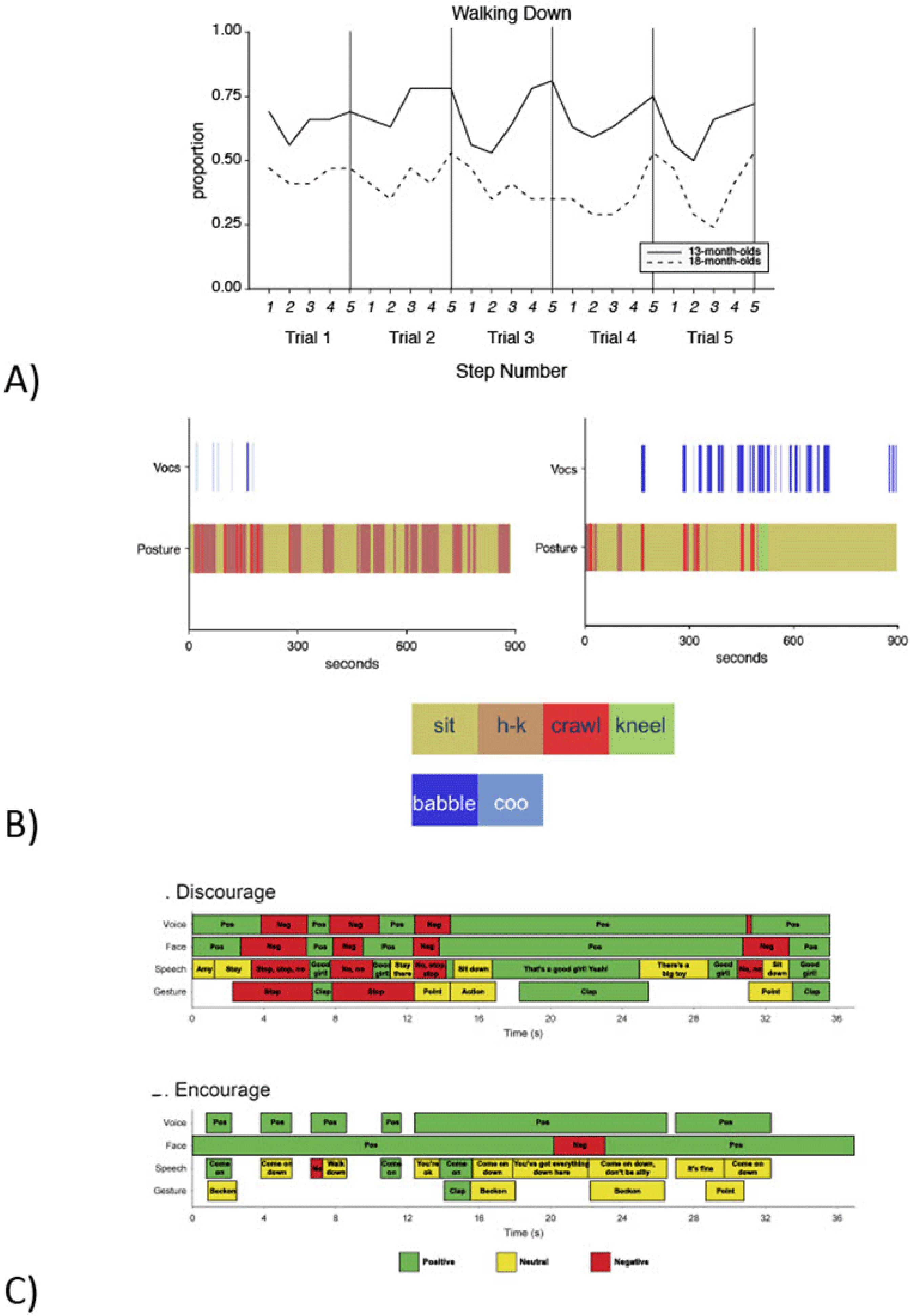
Walking Down
1.00
0.75
0.50
0.25
0.00
proportion
13-month-olds
18-month-olds
1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Step Number
A)
Vocs
Posture
0
300
600
900
seconds
sit
h-k
crawl
kneel
babble
coo
B)
Discourage
Voice
Face
Speech
Gesture
Time (s)
Encourage
Positive
Neutral
Negative
C)

Figure 1. Development unfolds in real time across a variety of contexts. (A) 13-month-olds (solid line) were more likely to try to walk down each step of a 5-step staircase and to return to walking at the start of each trial, despite walking being the least stable descent strategy; 18-month-olds (dashed line) were less likely to walk down each step over the course of a trial. (B) Exemplars of real-time crawling/vocalization trade-offs during a naturalistic play session showing that novice crawlers vocalize (blue vertical lines) less frequently while crawling (red) than when in other postures. (C) A mother of a typical 18-month-old coordinates multiple channels of communication with infants' own behaviors to discourage (top) and encourage (bottom) the infant to descend a sloping walkway.

Source: Figures adapted with permission from Berger et al. (2015, 2017) and Karasik et al. (2008).

Perception

The concept of the dynamic interaction of perception and action was pioneered by Eleanor J. Gibson (1988, 1994, 2000). She argued that infants learn to recognize possibilities for action (affordances) through physical interaction with and exploration of the world. The onsets of new motor skills like sitting and walking are "enabling" (p. 195) events that expand available perceptual information (Adolph, 2019). For example, infants' field of vision expands as they learn to turn their head (Lima-Alvarez et al., 2014), sit independently, and stand (Franchak et al., 2018). As infants' balance control during sitting improves and they rely less on supporting themselves with two hands (propped), they can engage in more object exploration. Increased object exploration after independent sitting is not merely a result of having hands free because even when they were supported by a researcher, 4- to 7-month-old propped sitters showed less physical, but more visual, exploration of objects than independent sitters (Marcinowski et al., 2019). Experienced independent sitters showed more simultaneous physical and visual exploration which, in turn, was linked to improved 3D object perception (Soska et al., 2010). As motor skills are automatized, infants allocate more attention to their perceptual experiences, which promote exploration and learning.

Reciprocally, perception also influences action. Visual information, for example, can motivate infants to move and practice independent locomotion (Atun-Einy et al., 2013; Franchak et al., 2018). Removing visual input by turning out the lights increased infants' instability when sitting (Kyvelidou & Stergiou, 2018) and reaching to grasp a toy (Babinsky et al., 2012). Vision and postural control are so tightly linked that when faced with visual information that conflicts with proprioceptive and vestibular information, visual information can be privileged. Infants compensate for virtual optic flow that suggests movement by making postural adjustments, even when their bodies are, in fact, stationary (e.g., Ueno et al., 2018). The real-time relationship between perception and action also describes how perceptual information is used in locomotor decision-making. Infants start by visually exploring their environment, followed by haptic or postural exploration if additional information is needed (Adolph et al., 2000; Kretch & Adolph, 2017). Ultimately the decision is made whether to proceed, devise alternative locomotor strategies, or avoid altogether. Whether this decision is successful depends on knowledge acquired over a longer timescale.

Motor Development "Day by Day"

While the interaction between motor development and other domains can unfold in the moment, interactions can also occur across longer timescales as infants gain motor experience over the course of days and weeks. The real-time sequence of exploratory behavior described in this article's subsection on "Perception" is necessary for gathering sufficient perceptual information to inform a motor decision, but it takes weeks of experience to know how to use that information adaptively (Kretch & Adolph, 2017).

Perceiving One's Own Abilities

Infants start reaching for their face and mouth in-utero (Sparling et al., 1999) and by the first few weeks of life have formed a sensory-motor connection between the movement of the hand and tactile sensation on the mouth (Lew & Butterworth, 1997). This sensory-motor connection is so well practiced that 7-month-olds tasked with locating vibrating tactile sensors on their face and mouth (figure 2) were just as accurate as 21-month-olds given the same task (Leed et al., 2019). However, younger infants could not successfully locate sensors on their arms. This decrement is not hypothesized to be due to reaching ability but rather inexperience in mapping tactile stimuli from that part of their body (Leed et al., 2019).

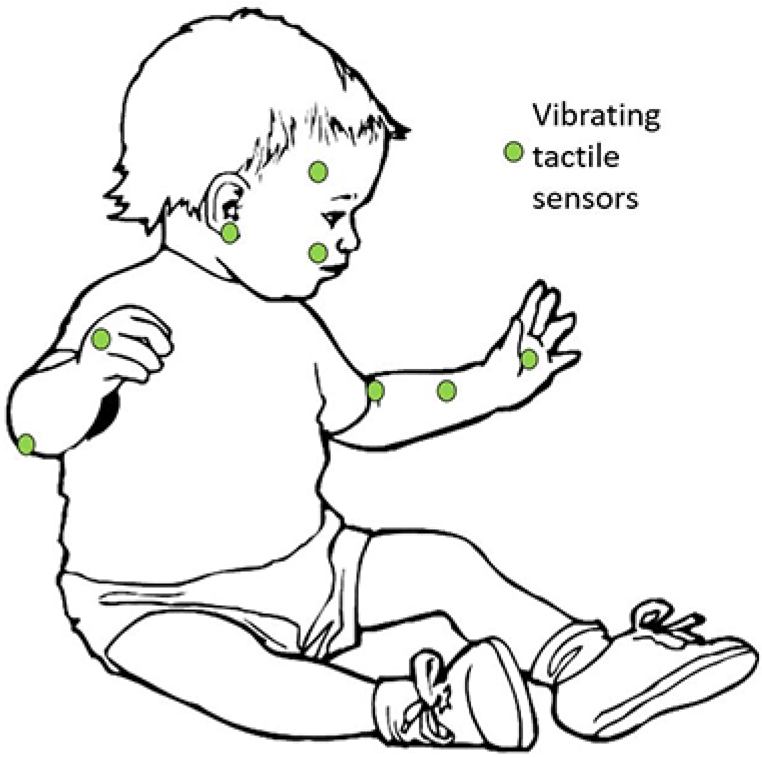

Figure 2. Depiction of the experimental protocol used by Leed et al. (2019). Infants and toddlers wore vibrating sensors and reached to locate the source of the tactile stimulation.

To expertly navigate the world—maintain balance, accurately judge risk—infants must "functionalize" perceptual information (Anderson et al., 2019). As defined by Anderson and colleagues (2019), "functionalization . . . requires mapping of the information onto adaptive control strategies involved in accomplishing goals" (p. 2). Posture-specific practice helps infants become attuned to and understand perceptual information, ultimately developing the expertise to determine what constitutes risk. However, perceptual knowledge gained from experience in an old posture does not transfer to a new one (Adolph, 2019). For example, weeks of cruising experience were not sufficient to prepare infants for walking without support (although infants may be strengthening their legs) (Adolph et al., 2011). Instead, cruising infants are in the process of mastering a highly specific motor sequence that hinges upon manual control of balance and an external, physical support. With the onset of each new skill, infants must relearn balance control and postural constraints anew.

Similarly, infants must learn to make meaning of perceptual information for depth in each new posture (Kretch & Adolph, 2013). In a classic series of experiments, infants were positioned on one end of a walkway, with a goal waiting at the other end, and some type of drop-off in between, such as a gap or a slope in the surface. In study after study, infants with many weeks of experience in one posture would avoid crossing or leaning too far over an impossibly large drop-off, but in their new posture those same infants attempted to cross the same wide gaps—even gaps that were wider than the infants were tall—for the toy (e.g., Adolph, 1995, 1997, 2000). The same infants would make good decisions as experienced sitters, but bad decisions as novice crawlers; good decisions as experienced crawlers, but bad decisions as novice walkers. Novices would crawl or walk right over the edge and need to be rescued by an experimenter (see Adolph & Hoch, 2019; Adolph et al., 2021 for reviews).

One controversy in the literature stems from studies that appear to show instances when perceptual knowledge does transfer from crawling to walking (e.g., Burnay et al., 2020; Witherington et al., 2005). New walkers with more crawling experience avoided ostensibly risky situations more often than new walkers with less crawling experience. A key methodological difference is that these studies generally ask infants to make decisions about crossing *apparent* drop-offs, such as a drop-off into water, rather than thin air, or Eleanor J. Gibson's classic visual cliff (Gibson & Walk, 1960) that looks like a gap in the walkway, but actually has safety glass. Originally, researchers thought they were studying the development of depth perception in infancy (Walk & Gibson, 1961), but decades of research has revealed that infants perceive depth well before they can crawl. Infants learn the meaning of depth—consequences of falling—from self-produced locomotion (e.g., Adolph, 2000). How conflicting perceptual information—visual information about depth along with haptic information about the glass or water—impacts locomotor decision-making, as well as what constitutes ecological validity, remains to be understood.

Locomotor experience also contributes to changes in infants' understanding of peripheral lamellar optic flow, which supports visual proprioception. For example, hands-and-knees crawlers reacted with more postural adjustments to movements of the walls and ceiling of a moving room than belly crawlers or pre-crawlers with comparable crawling experience (Anderson et al., 2019; Ueno et al., 2018). Hands-and-knees crawling places more demands on balance control than belly crawling, which, in turn, provides more experience using visual information in support of balance control. Differences in perceptual understanding may also stem from belly crawling being more effortful than hands-and-knees crawling, thereby leaving fewer attentional resources available to attend to perceptual information.

Sleep

Even incremental change in motor skill can have a cascading influence on other areas of development (Horger & Berger, 2019). Typically, these changes are considered positive, such as new opportunities for interacting with the world. However, acquisition of new motor skills can also be associated with regressions to less mature behavior. For example, the onset of new locomotor skills has been associated with disruptions to infants' sleep. Infants who had begun crawling had more fragmented sleep, more episodes of prolonged awakening, and more activity during sleep, than age-matched controls who had not yet begun to crawl (Scher, 2005; Scher & Cohen, 2005). Moreover, the timing of skill onset can change the developmental trajectory of sleep patterns. An increase in long nighttime wake episodes spiked for early crawlers at crawling onset, whereas long night wakes episodes increased gradually over the transition to crawling for infants who learned to crawl later (Scher & Cohen, 2015). Similarly, infants who were younger than 8 months when they first learned to pull to a stand had an increase in night wakings and a decrease in sleep efficiency upon skill onset. In contrast, infants who were older than 8.6 months when they first pulled to stand showed no disruptions to sleep associated with skill onset (Atun-Einy & Scher, 2016). Infants' sleep may be disrupted upon the onset of new motor skills due to learning-related neural reorganization during REM sleep (Cao et al., 2020).

The relation between sleep and motor development is bidirectional. Not only does changing motor ability impact sleep, but sleep, in turn, can impact motor ability. For example, the quality of sleep the night before learning a novel locomotor problem predicted newly walking infants' readiness to learn (Horger et al., 2021). Of the infants who ultimately solved the task, which involved inhibiting walking in favor of crawling, the more wake episodes and less efficient their sleep the night prior, the greater their difficulty in solving the problem the next day. One function of night sleep is to reset synaptic strength after a day of learning to prepare for the next day's learning (Tononi & Cirelli, 2014). Newly walking infants who napped during a delay between training and test solved a locomotor problem more efficiently at test than those who stayed awake during the delay (Berger & Scher, 2017). Napping may protect new skill acquisition from interference and/or actively consolidate new information (Horváth & Plunkett, 2018).

Social Cognition, Communication, and Language

Developmental changes in infants' motor skills can affect developmental changes in social-cognitive exchanges and language. The transition from crawling to walking literally affects what infants see, what they play with, and how they communicate with caregivers. While crawling, infants are limited to what's at hand: the floor in front of them, the objects nearby, and caregivers' faces, but only if caregivers stoop to interact (Franchak et al., 2018; Kretch et al., 2014). Once infants begin to walk, their physical and social world expands: They see wider arrays, travel greater distances, contact distal objects, and engage with caregivers in new ways (Adolph et al., 2012; Karasik et al., 2011, 2014; Kretch et al., 2014). Once infants were able to walk independently, they walked to get to objects in different rooms, carried them to new locations, and shared them with caregivers (Karasik et al., 2011; Karasik et al., 2012). But when infants were only able to crawl, they seldom moved distances, contacted objects in the vicinity, and shared those objects with caregivers while remaining in place. This qualitative shift in object sharing created new opportunities for social interactions (Karasik et al., 2014). When infants carried objects over to their mothers to share them, mothers responded with complex action directives (e.g., let's read), and with simpler object labels when infants shared in place (e.g., that's a book).

Theoretical and empirical accounts support links between walking onset and communicative skills (Iverson, 2010). For example, researchers have noted coupling between rhythmic arm movements and reduplicated babbling, manual gestures and vocabulary, and object mouthing and early vocalizations (Iverson et al., 2007). Perhaps because of these bidirectional and systemic changes from motor development, to social communication, to caregiver response, the transition to walking has been argued to bring about linguistic benefits. In longitudinal and age-held-constant designs, researchers reported significant increases in vocabulary for walkers over crawlers (He et al., 2015; Walle & Campos, 2014), although this finding is inconsistent within and across labs (Moore et al., 2019; Walle & Warlaumont, 2015). So, being able to travel more, see farther, and carry and share objects with caregivers thereby eliciting different responses may give walkers an advantage in their language development.

Infants' motor development shapes their use of social information when making motor decisions in potentially risky situations. Researchers tested crawling and walking infants' use of social information from their mothers when deciding when to descend safe and risky slopes and cliffs. On some trials, mothers encouraged their infants to crawl or walk down, and on other trials mothers discouraged crawling or walking (figure 1C) (Karasik et al., 2008). Experienced 18-month-old walkers selectively used social information only on slopes and cliffs that were ambiguous (Karasik et al., 2016), but on clearly safe and risky slopes and cliffs they disregarded mothers' encouraging and discouraging messages. Expert 18-month-olds updated their reliance on social information when their motor skill was hampered with slippery Teflon-soled shoes. Now that their walking skill was diminished—infants were only able to successfully descend slopes that were 9° as compared to 24° when barefoot—they relied on mothers' messages almost exclusively (Adolph et al., 2010). Mothers also took infants' motor expertise into account, tailoring their encouraging and discouraging messages to infants' age and locomotor experience (Karasik et al., 2008). Mothers referred to actions more frequently when communicating with 18-month-olds as compared to 12-month-olds and more frequently to expert crawlers as compared to novice walkers.

Culture and Individual Differences in Motor Development

Cross-cultural research further illustrates the social and contextual influences on motor development, highlighting individual differences. Much of the work on infant motor development has been conducted in Western populations, overlooking cultural influences, assuming universals. In fact, researchers have taken childrearing practices for granted, considering variability in childrearing as a nuisance rather than as important differences in infants' experiences, which offer unique opportunities for posture, balance, and locomotion. The effects of everyday experiences are most clear in cross-cultural comparisons. Cultural research illustrates the formative role of experience in motor development, thereby challenging our assumptions that differences in childrearing have no effects on motor development.

Culture Informs Parenting Practices

Childrearing practices—how caregivers handle, position, and dress their infants—can profoundly affect infant motor development by facilitating or constraining opportunities to move (Adolph et al., 2010; Adolph & Hoch, 2019; Adolph & Robinson, 2015; Karasik, 2018). In some African and Caribbean cultures, caregivers prop infants in sitting positions or hold them upright to encourage stepping from birth; in turn, infants sit and walk at earlier ages than do infants of caregivers who do not engage in such practices (Bril & Sabatier, 1986; Hopkins & Westra, 1988, 1989, 1990; Konner, 1976; Super, 1976). Experimental studies with Western infants confirm the benefits of enhanced practice (Libertus et al., 2016; Lobo & Galloway, 2012; Zelazo et al., 1993; Zelazo et al., 1972). Conversely, limited opportunities to move—such as in the Ache of Eastern Paraguay where caregivers often carry their infants and rarely set them down—result in delays in infant motor skills relative to U.S. norms. Ache children begin to walk independently at 21–23 months, 9 months later than specified ages on standard assessments and a full year later than reported in some African cultures where stepping is practiced (Kaplan & Dove, 1987; Konner, 1976).

Similarly, differences in positioning of infants—laying babies supine for sleep and wake—can delay rolling, crawling, and other prone skills (Davis et al., 1998). Caregivers who encourage "tummy-time" to compensate for infants' limited prone experience have infants who begin crawling at earlier ages than infants who spend less playtime prone (Dudek-Shriber & Zelazny, 2007). In northern China where water and diapers are scarce, infants lay supine for hours in a bag of fine-grained sand to absorb waste—a toileting practice called sandbagging. Sitting and walking was delayed by weeks to months in infants whose caregivers used sandbags compared to infants who were not placed in sandbags (Mei, 1994).

Clothing and diapering likewise can affect infant motor development. Bulky clothes worn during colder seasons prevent crawling infants from freely moving on hands and knees (Benson, 1993; Fung & Lau, 1985; Hayashi, 1992) and while wearing a diaper, infants walked slower, had shorted step length, and displayed more gait disruptions compared to when they walked naked (Cole et al., 2012).

In Tajikistan, caregivers have solved the problem of containment, dressing, sleeping, and toileting all at once. For generations, caregivers in Tajikistan and surrounding areas have used a "gahvora" cradle in which infants are bound head to toe. In the cradle in figure 3, infants lie swaddled in a supine position, with arms tightly bound to their sides and legs secured together so that head, arm, torso, and leg movements are severely restricted (Karasik et al., 2018). Drapes extend the length of the gahvora, often covering infants' faces. Infants remain strapped to the gahvora even during feeding and toileting. An external catheter drains waste from infants' bodies into a bowl underneath the cradle.

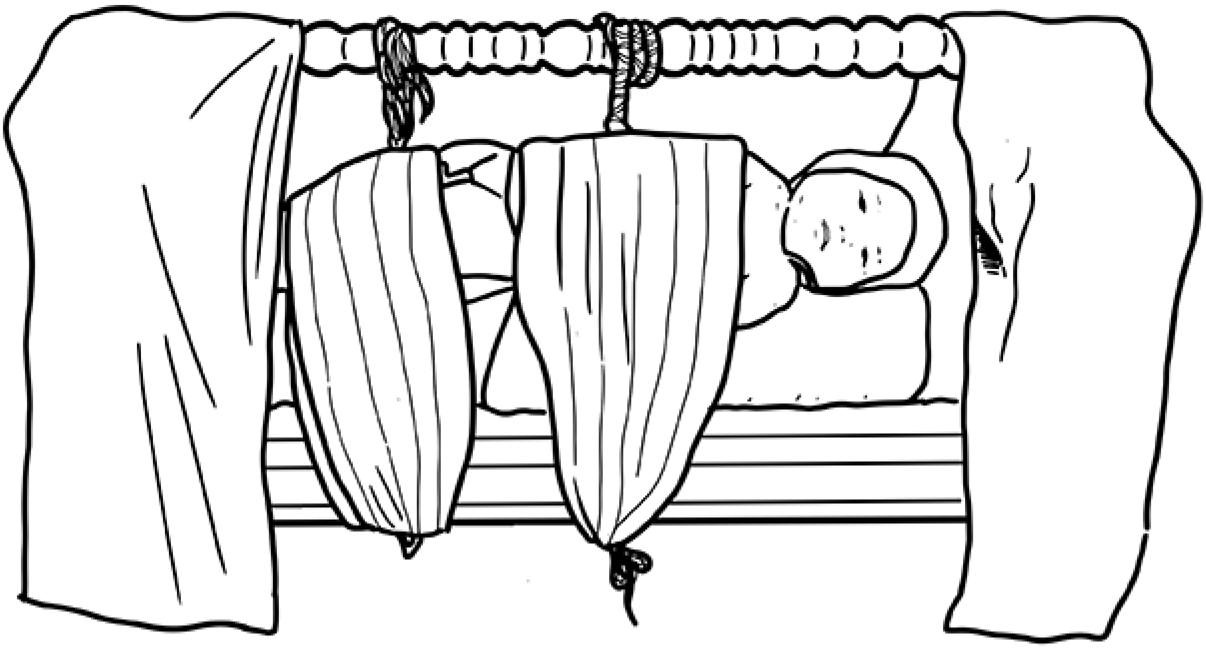

Figure 3. Infant tightly bound in the gahvora; top and bottom drapes are drawn to block light and draft. An external catheter (not shown) placed over genitals drains waste into a special bowl placed under the cradle.

Gahvora cradling has survived thousands of years, and, thus, must yield benefits that outweigh any potential deleterious effects. Caregivers readily noted that gahvoras lull infants and get infants to sleep and prolong their sleep, which in infancy is particularly important for learning (Berger & Scher, 2017; Horger et al., 2021). Even when infants are awake, gahvoras function like a playpen, containing infants when caregivers must complete tasks or leave the room. Gahvoras help protect infants from harsh environmental conditions (e.g., livestock, open fire pits for cooking, harsh weather). Also, gahvoras keep infants clean, as they serve as a toileting method in an area with limited access to alternatives such as diapers and clean water.

Gahvora cradling is widespread. But the amount, distribution, and developmental changes in cradling vary widely from family to family (Karasik et al., 2018). Some infants spend almost a full 24-hour day in the gahvora, but others spend only an hour or 2. Some infants are cradled largely during the night, some primarily during the day, and others in bouts distributed across day and night. And some infants stop cradling in the first year, whereas others are cradled well into the second and even third years.

Researchers have begun to test the role of restricted movement on motor and physical development in healthy infants reared in loving homes. That is, despite the physical restriction associated with the gahvora, infants in Tajikistan are immersed in family life, surrounded by children, caregivers, and other adults who affectionately respond to infants' needs (Karasik et al., 2018). Thus, unlike studies of children reared in orphanages (Roeber et al., 2012) or under other extreme cases of deprivation (Dennis, 1960; Kennedy et al., 2016), the physical restriction of gahvora cradling is not confounded with social deprivation. Moreover, the unique, largely unstudied experience of gahvora cradling allows researchers to rigorously test a powerful developmental rule of thumb—that practice with a motor skill predicts motor skill proficiency, regardless of the timing of that skill. Researchers are finding that even though infants display later onset ages and lower proficiency of infant motor skills relative to established norms on average, differences among infants in motor skill experience predict locomotor proficiency, similarly to Western samples (Karasik, Fernandes et al., 2021).

Similarly, motor experience seems to mitigate delays in infancy and perhaps explain the comparable skills in early childhood. Despite extensive cradling in infancy and lags in motor skill onsets and proficiency, differences between Tajik and U.S. children were negligible. Sheer maturation is not sufficient to explain the seeming "catch up" effect. A likely explanation is the presumed variable motor practice children take advantage of once gahvora cradling stops, usually after the second or third year of life. Indeed, practice was a stronger predictor of motor proficiency than chronological age (Adolph et al., 2003). Researchers' observations of children's everyday activities suggest that once infants become mobile, albeit delayed, their movements are highly unrestricted. By 2 to 3 years of age, children are allowed tremendous amounts of freedom to move. They travel freely from inside and outside contexts of their homes, have access to a variety of surfaces and elevations, and travel around their village with minimal adult supervision. Studies have shown that exposure to nature is associated with cognitive functioning like attention and creative reasoning Atchley et al., 2012; Schutte et al., 2017). Tajik 3-year-olds roam, climb high ladders, use heavy farm tools, and wield sharp objects. These highly specialized skills do not appear on any standardized test. The culturally relevant experiences hone children's skills—if compared with U.S. children, Tajik children would likely outperform.

Culture Informs Opportunities for Movement

Within-cultural differences can also drive variability in motor development. For example, whether families in the United States had stairs in their home was related to how old infants were when they learned to climb stairs independently, the strategies that infants used when they learned to descend stairs, and whether infants' parents taught them how to descend stairs (Berger et al., 2007). Infants who lived in homes with stairs learned to ascend about a month earlier than infants who lived in homes without stairs—10.5 months on average, as compared to 11.4 months. But access to stairs is not the only determinant of when infants learn to climb stairs. Regardless of whether infants had stairs in their home, there was no age difference in when they learned to descend. The difference between average of onset for ascent and descent reflected parents' constraints on access—even when infants lived in a home with stairs, their parents restricted their access until they were confident that infants were safe. Parents preferred that infants back down stairs and taught that method more than other descent strategies. However, backing is a challenging strategy because it requires infants to turn away from the direction they are headed. As long as parents insist on infants using that strategy, there will almost certainly be a lag between ascent and descent onsets. Stair-climbing is an interesting motor milestone because onset stems from a unique combination of motor, cognitive, and social factors. Learning to climb stairs serves as a vivid illustration of how culture and environment shape opportunities for movement and affect the "when" and "how" of motor skill acquisition.

Opportunities for movement, exploration, and play are further illustrated when considering furnishings and artifacts found in homes. Across cultures, caregivers devise ways to contain infants while awake and asleep to keep them safe, occupied, and comfortable. Various containments in which infants spend time place different constraints on posture, body, and limbs and thus affect daily practice with posture and locomotion. There are, in fact, many containments in which infants in the United States spent time during a typical day. When awake, 12-month-olds in the United States spent time in seven containments and 5 hours in restricted settings distributed over the day as compared to only two containments and 2 hours for Tajik infants (Karasik, Kuchirko et al., 2021). Perhaps the lack of restrictions outside of the gahvora may explain the catch-up effect for Tajik infants' motor skills.

The natural settings in which motor skills emerge and develop are meaningful. Take sitting, for example. The accepted practice for 5-month-olds is to be strapped into infant car seats or held in caregivers' arms. Perhaps the cultural expectation about infants' fragility and lack of skill guides caregivers' behaviors of staying nearby, never leaving an unattended infant seated on a raised surface like a bed or couch. However, mothers from Kenya and Cameroon spent considerable time out of reach of their sitting infants (Karasik et al., 2015). Baganda mothers in Uganda take a concerted effort to train their infants to sit starting from 3 months of age by placing infants in a dug-up hole in the ground to practice keeping balance (Klibride & Kilbride, 1975). As a result, the Baganda infants demonstrate independent sitting a month earlier than their American counterparts. Given the cascading effects of sitting into other domains like perception and cognition, the Baganda infants' developmental trajectory could be shifted in favor of perceptual and cognitive skills as described in the previous section.

The objects for exploration and play guide infants' learning. Although play occurs across cultures, infants' playthings vary enormously and in turn may affect infants' learning through object play. In a 2-hour naturalistic observation at home, researchers tallied all objects—child-intended toys and other hand-held manipulatives—that U.S. infants contacted for play (Herzberg et al., 2021). Infants spent half their observation time in manual contact with objects and held 14 different types of objects designed for children (e.g., books, puzzles, push toys, etc.) not including all other manipulatives (e.g., kitchen items). How ubiquitous then is object play in rural Tajikistan, for example, where toys may be less prevalent and childrearing practices may overlook the importance of play? Despite the scarcity of toys, Tajik infants spent a comparable amount of time engaged with objects (Karasik, Schneider et al., 2021). Walking infants in particular, took it upon themselves to discover available objects, indoors and outside, often relating objects to each other (e.g., finding pebbles to fill a household container). Crawlers also engaged with objects, but their object access relied on caregivers. Together, these examples illustrate the dynamic nature of cultural practices and the intersection of behavioral domains of infants. Moreover, these studies show that the variability in motor skills, which has been documented since Gesell, can be attributed to culture and context. Specifically, caregivers' expectations—the choice to train motor skills—and childrearing practices—use of containments, access to objects—in part, explain how cultural differences in motor development manifest.

Standardized Motor Assessments: Alberta Infant Motor Scale

In stark contrast, standardized motor assessments identify delays or precocities without giving credit to the underlying mechanisms of those outcomes. Classic assessments that fall victim to this critique are the Bayley, Denver, Griffith, and Brazelton scales, to name a few. A more current version typically used in North America is the Alberta Infant Motor Scale (AIMS). It was developed and normed in Canada in the early 1990s and primarily relies on observation (Piper et al., 1992). Based on this sample, early cutoffs to indicate a delay were established as below the 10th percentile at 4 months and below the 5th at 8 months (Darrah, 1998). Since then, the AIMS has been translated many times to expand its application cross culturally, as seen in figure 4. Translation requires significant effort to ensure linguistic and conceptual continuity (Aimsamrarn et al., 2019). However, researchers in Brazil and the Netherlands have consistently found that the "standardized" norms did not fit their specific population distributions and altered them (Saccani et al., 2016; van Iersel et al., 2020, respectively).

Other researchers found differences in samples of infants from other countries when compared to the Canadian norms, but only at specific ages. In Turkish infants, the discrepancies appeared in the earliest motor skills but were resolved by 3 months (Kepenek-Varol et al., 2020). South African infants diverged at 4 months and converged again around 8 months (Manuel et al., 2012). Norwegian infants showed lower scores toward the end of the first year (Størvold et al., 2013), and Thai infants scored below the norm early in life and then above at 7-, 11-, and 13 months (Tupsila et al., 2020).

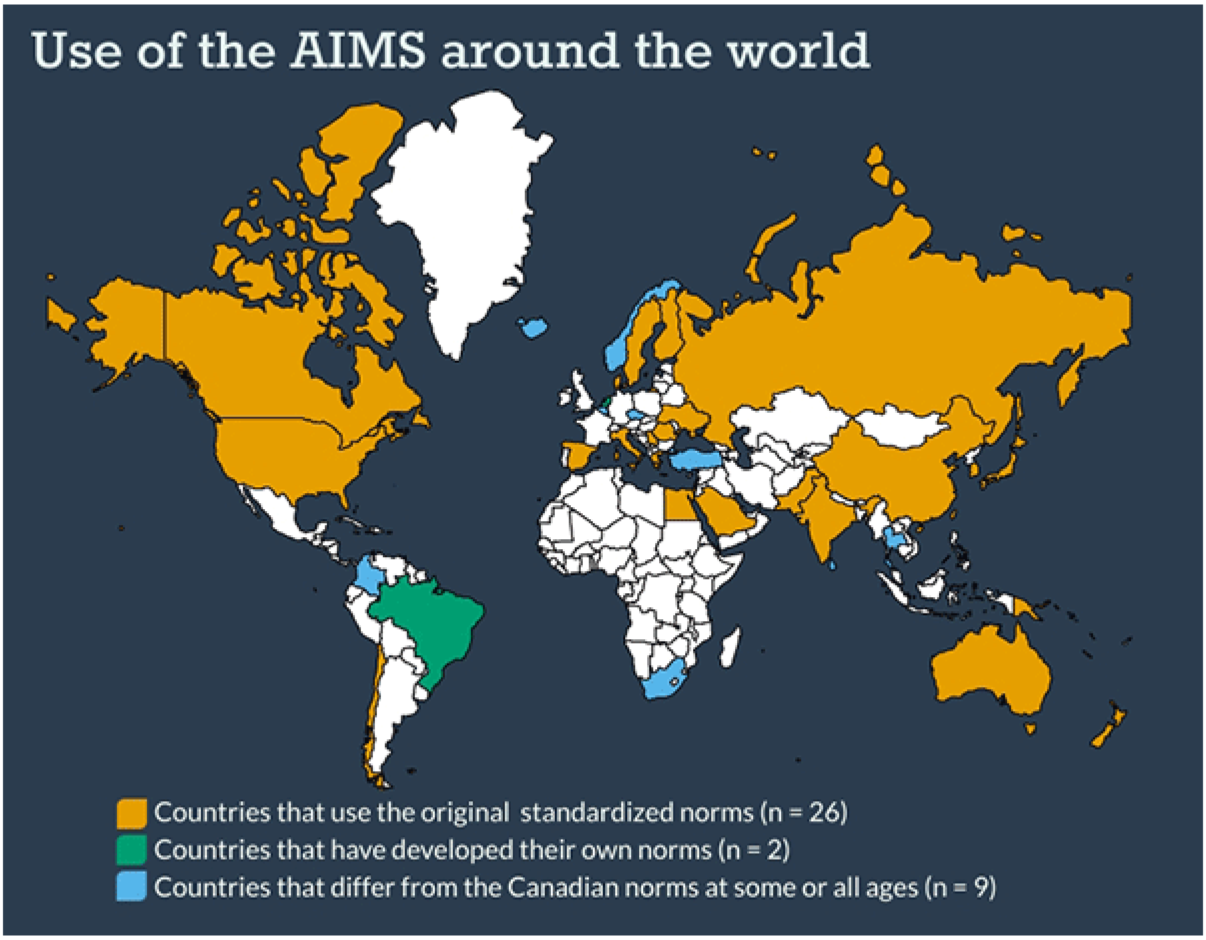

Figure 4. Map of countries (N = 37) that have used the Alberta Infant Motor Scale (AIMS) for research. Countries are color-coded by use of Canadian norms.

Note: See Table 1 for all countries and corresponding references.

The primary issue with inaccurate AIMS norms is over- or under-diagnosis of motor delays. Under-diagnosis obscures the efficacy of early intervention. Over-diagnosis could place strain on a system with limited resources. An infant's percentile on the AIMS only reflects one moment in time, but if it falls below a designated threshold, infants could be flagged as having a motor delay. The impact of such a diagnosis and subsequently available services vary worldwide. Sometimes infants are assessed again, but, more commonly, the scores are used as a one-time qualifier. This is not recommended because of intra-individual variability. When a group of healthy, full-term infants was assessed with the AIMS monthly until 18 months, about a third of them scored in the lowest 10% at some point during their participation interval. From month to month, one infant's scores fluctuated as much as dropping by 50% (Darrah et al., 1998).

The question of how to properly adjust norms is not straightforward. One challenge to country-specific norms is accounting for immigration and increasingly diverse populations (Mendonça et al., 2016). Another hurdle for standardized motor assessments more broadly is incorporating culturally relevant materials and questions. The AIMS accounts for this by using naturalistic observation and trained behavioral coders. At no point in its translation or the development of new norms have the procedures or descriptions of motor skill been altered.

Table 1. List of Citations and Country of Origin Included in Figure 4 "Use of the AIMS Around the World."

Generalizing Motor Development Research

The last hundred years of research have expanded knowledge of motor development but have not resolved all critiques of Gesell and other early researchers. Most notably is the extent to which knowledge can be generalized. When culture, race, or ethnicity are not variables under direct consideration, they are often disregarded (Nielsen et al., 2017). The studies summarized in the first section (*N* studies = 66; *N* infants = 5,262) that investigated the relationship between motor and other developmental domains mostly described the development of an ethnically uniform sample or did not describe the background of the sample at all (see figure 5). Race and ethnicity are not hypothesized to directly influence motor development but rather to do so indirectly via social and cultural factors (Mendonça et al., 2016). Documenting and diversifying sample populations is necessary to improve the generalizability of motor development research.

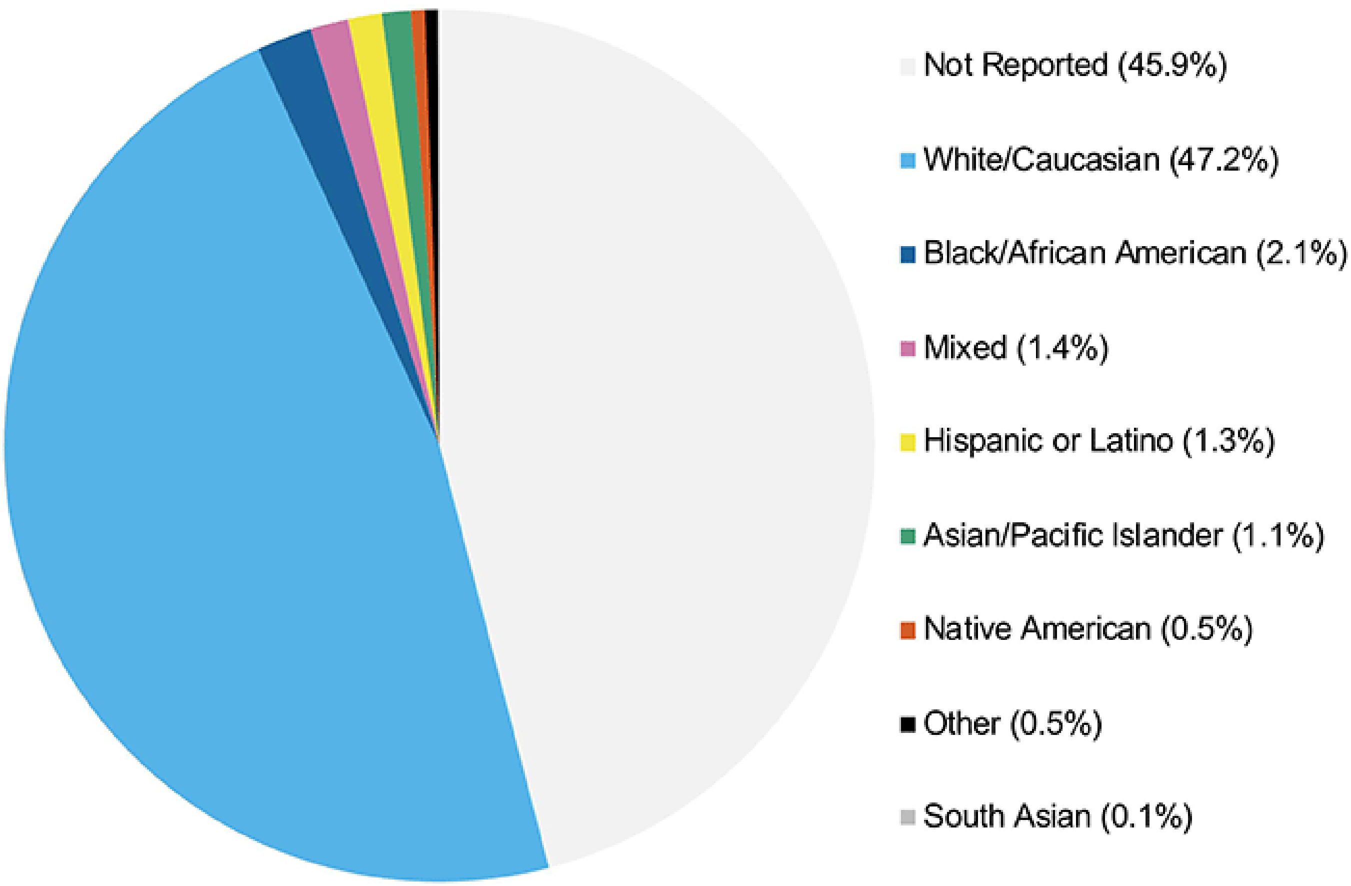

Figure 5. Race and ethnicity of infants in a representative sample of motor development research. It does not include cross-cultural studies whose purpose was to explicitly compare ethnocultural groups.

Note: The 66 studies included in this sample are marked with an * in the reference section.

Conclusions

Because motor skills are directly observable, motor development serves as a useful exemplar for general principles of development. By contrasting current frameworks with more traditional approaches, this summary of motor development has prioritized the interaction between motor development and other psychological domains, such as language, cognition, perception, sleep, and culture, to portray a realistic picture whereby changes across domains happen simultaneously and shape one another. These context-specific interactions unfold in the moment, day by day, and over a lifetime. Knowledge of motor development is largely based on the study of a homogeneous population, but it is argued here that such knowledge has been overgeneralized and treated as a universal process. Closer inspection reveals that individual differences are the only “norm” of motor development.

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