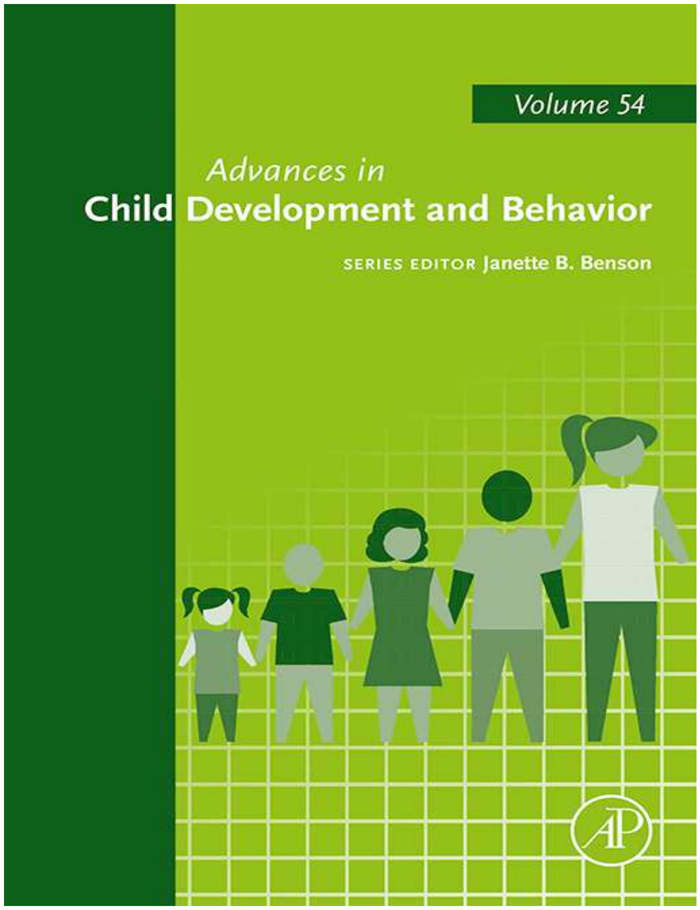

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CHAPTER TWO

Cognition–Action Trade-Offs Reflect Organization of Attention in Infancy

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Abstract

This chapter discusses what cognition–action trade-offs in infancy reveal about the organization and developmental trajectory of attention. We focus on internal attention because this aspect is most relevant to the immediate concerns of infancy, such as fluctuating levels of expertise, balancing multiple taxing skills simultaneously, learning how to control attention under variable conditions, and coordinating distinct psychological domains. Cognition–action trade-offs observed across the life span include perseveration during skill emergence, errors and inefficient strategies during decision making, and the allocation of resources when attention is taxed. An embodied cognitive-load account interprets these behavioral patterns as a result of limited attentional resources allocated across simultaneous, taxing task demands. For populations where motor errors could be costly, like infants and the elderly, attention is typically devoted to motor demands with errors occurring in the cognitive domain. In contrast, healthy young adults tend to preserve their cognitive performance by modifying their actions.

Attention is necessary because at any given moment the environment presents far more perceptual information than can be effectively processed, one's memory contains more competing traces than can be recalled, and the available choices, tasks, or motor responses are far greater than one can handle.

Chun, Golomb, and Turk-Browne (2011, p. 75)

1. INTRODUCTION

Imagine you need to use a rental car which is unlike your own car, and you need to drive from the rental agency to your workplace. Because the operation of the vehicle is new, and the most direct route to your work is unfamiliar from the rental agency, you might make the choice to drive a longer route that is familiar. You have decided to allocate attention to operating the newly obtained and unfamiliar car (a motor task), so you do not have to attend to the cognitive choices necessary to locate a new route to your destination. Consider also a case where there is no option to intentionally allocate attention under taxing conditions. Imagine leaving work with plans to run an errand on the way home. Unexpectedly, weather conditions turn hazardous with poor visibility and slippery roads. Suddenly you find yourself at home, rather than at the store as intended. Maintaining vigilance for potential hazards while performing the motor task of driving elicited a perseverative response, an inability to inhibit taking the usual route home. The recruitment of resources for sustained visual attention and motor reactions resulted in a trade-off: cautious, deliberate driving at the expense of keeping an infrequently used route simultaneously in mind.

Many daily situations offer examples of resource allocation. Examples include stabilizing posture by sitting down in order to think through a math problem, or requesting quiet in order to perform a difficult motor task. Across the life span, the decisions to focus attention on either a motor skill or a cognitive skill depend on the task goal, prior practice, and environmental supports. How do infants develop the ability to move in a coordinated way around the environment while talking and planning their creative play games? And how do they do so in a continually changing body with changing skills and expertise? We aim to trace the origin of this smooth allocation of attention and resources from infancy through adulthood, describe a set of principles supported by evidence to understand development in typically developing children, and conclude by proposing strategies that may support children with motor or cognitive differences and delays.

We start by defining what aspects of attention comprise the discussion. This is necessary because attention is a central feature of all perceptual and cognitive operations (Chun et al., 2011). We certainly do not propose to summarize the development of all aspects of attention in one chapter. Instead, we focus on a key aspect of attention that pertains directly to the immediate concerns of infancy—fluctuating levels of expertise, balancing multiple taxing skills simultaneously, learning how to control attention under variable conditions, and coordinating distinct psychological domains. These functions fall under the subcategory of internal attention[a] which includes the cognitive control or executive processes of working memory, decision making, and responding (Chun et al., 2011). This category structure of attention serves our purposes because the distinction is based on the targets of attention. This dovetails with our synthesis of the literature on the development of allocation of attention—where attention is targeted—in infancy.

With our busy lives, we may think it necessary and efficient to multitask, and we may even think that we are good at attending to several things at once. But in fact, attention has both functional and physiological limitations (see Chun et al., 2011, for a review). Attention is a fixed resource that allows for the selection and processing of information (Kahneman, 1973; Lavie, 2005). Executive control is responsible for directing attention to relevant and useful information, away from irrelevant information, and for inhibiting extraneous stimuli (Roderer, Krebs, Schmid, & Roebers, 2012).

[a] As opposed to external attention, which we do not address in this chapter, and which pertains to sensory or perceptual attention.

This executive control system is most taxed as individuals attempt to multitask and divide their attention as it is needed for either information selection or deciding an action strategy, and it is this system that we consider primarily as part of the cognition–action trade-off seen in functional interactions of the growing child within the environmental milieu.

2. NEURAL CORRELATES

Attention is comprised of three anatomically distinct, underlying brain networks that serve specific functions: orienting, alerting, and executive control (Posner, 2016). These networks of attention have been identified by brain imaging using visual or auditory paradigms. The orienting network, primarily responsible for covert attention and eye movements, is comprised of the inferior and superior parietal lobe and frontal eye fields (see Fig. 1). The alerting network lies in the right hemisphere of the frontal and parietal cortex and serves to produce and maintain optimal levels of arousal and performance, a necessary prerequisite for other attention functions (Petersen & Posner, 2012). The executive control network is linked to traditional executive functions such as decision making and inhibition and stems from the medial frontal cortex and anterior cingulate cortex (Petersen & Posner, 2012; Posner, 2012).

The sharing of attention is supported by studies of neural processes during dual or complex tasks to determine the underlying mechanism of resource

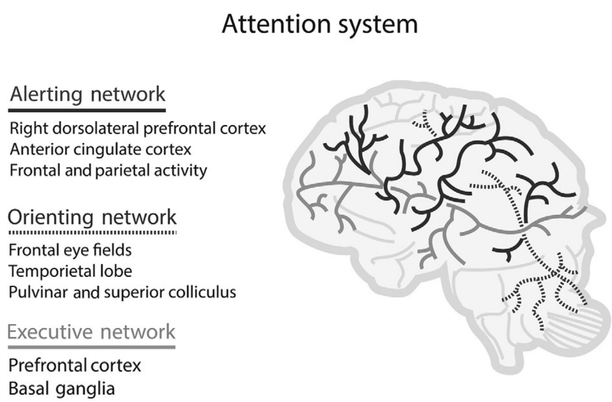

Fig. 1 Depiction of the alerting (*black*), orienting (*dashed*), and executive (*gray*) networks that comprise the attention system. *Reprinted with permission from Posner, M. I., Rothbart, M. K., & Rueda, M. R. (2014). Developing attention and self-regulation in childhood. In A. C. Nobre, S. Kastner, A. C. Nobre, & S. Kastner (Eds.),* The Oxford handbook of attention *(pp. 541–569). New York, NY: Oxford University Press.*

allocation. Due to the current limitations of brain imaging technology, the paradigms designed to examine attention sharing do not allow the individual being studied to move in a natural manner. Although our specific interest involves tasks consisting of a motor and cognitive component, we will describe possible neural mechanisms using a dual-task paradigm with other systems (e.g., vision and cognition) to understand how the brain processes information or selectively attends to competing features of a given task.

During the first year of life attention evolves from an emphasis on the early, more primitive systems of alerting and orienting, to the executive system, considered to be responsible for more complex functions. Visual attention is selective from birth, notable in infant preferences for looking at faces and contrasting objects (Fantz, 1961), and is thought to be initially under the control of the alerting and orienting systems of attention. The orienting network becomes coordinated during early development to connect eye, head, and attentional shifts. During the first few months, visual attention changes such that long looks to people and objects begin to shorten, and infants switch gaze from object to object with greater ease. Interestingly, at 5 months of age, the ability to disengage from one visual fixation and switch looks to another fixation predicts later attentional abilities (Bornstein, 1990). Infants whose attention style was categorized as efficient at information processing (switching gaze) at 5 months of age had better executive functioning at 2, 3, and 4 years of age than infants whose attention style had been slow to process information at 5 months (Cuevas & Bell, 2014). These studies support the idea that the maturation of the executive type of attention facilitates cognitive control and decision making and predicts later indices of cognitive functioning (Colombo, 2001; Coomans, Vandenbossche, & Deroost, 2014; Diamond, Carlson, & Beck, 2005). The executive system of attention begins to emerge around the time when infants can manipulate objects (Ruff & Rothbart, 2001). Other motor skills emerge concurrently with object manipulation, including postural control of the sitting position, skillful reaching, and precursors to mobility and transitional movements (Harbourne, Lobo, Karst, & Galloway, 2013). The explosion of new motor skills in infancy invites interaction with the environment and necessitates interaction with the executive attentional system. Although maturation occurs concurrently in all systems, the visual attention system and motor control systems support each other in an iterative process as the infant engages with the world (Harbourne, Ryalls, & Stergiou, 2014).

The majority of studies investigating the functional aspects of attention at all ages include visual orienting or visual discrimination of selected objects, which translates to navigating a natural environment embedded with important targets that must be selected and prioritized for a specific goal (Peelen & Kastner, 2014). For example, an older child or adult may need to scan the environment for oncoming vehicles when crossing the road. This "natural" task may be simulated in the lab by asking the participant to scan a screen for a specific item among various types of distractors. This task would require eye movements, attention, and cognitive skills, but disallow large movements of the participant. Some general findings in studies with adults indicate that the brain utilizes multiple mechanisms that serve to selectively enhance information that is most relevant to the goal at hand (Greene, Murphy, & Januszewski, 2017; Petersen & Posner, 2012; Posner, Rothbart, & Rueda, 2014). These neural strategies are built over time by building long-range connections between the prefrontal cortex and the visual areas of the brain. The prefrontal cortex is involved in planning and cognitive tasks, as well as planning movements. The prefrontal area undergoes extensive change during early development. Simple maturation does not explain the dynamic and flexible allocation of resources and the various timescales that affect the sharing of attentional resources. For example, unlike children with normal hearing, children with a hearing impairment show increased activation of the part of the brain that engages for visual peripheral motion detection, the medial temporal area. This brain difference supports the behavioral finding that children with a hearing impairment tend to have both greater distractibility and, at the same time, greater attention to surrounding visual stimuli, which logically may be an adaptation to the deficit that is manifest by the ability to pick up information through the auditory system (Dye, Hauser, & Bavelier, 2008). Such adaptations, which amplify or inhibit specific components of attention, serve to support the concept that the allocation of attention adapts over developmental time to support individual needs.

Current theory proposes that attention, in a top-down manner, serves to boost certain representations and dampen others, such that there is an ongoing, dynamic allocation of resources when there is competition during a given task (Buschman & Kastner, 2015). This modulation of brain areas, neural networks, single neurons, and connections of neurons is strengthened with repeated attention, resulting in boosted signals as attention is allocated either to perceptions and sensory information that is external or to internal goals of the individual (Buschman & Kastner, 2015). Adaptation due to constraints unique to the individual contributes to the selection process, and factors into the variation seen in specific developmental differences or diagnostic categories (Johnson, Jones, & Gliga, 2015). This dynamic process of adaptation during attention allocation may explain differences in developmental trajectories over the course of childhood into adulthood.

3. DEVELOPMENTAL TRAJECTORY OF DUAL-TASK PERFORMANCE

The dual-task paradigm has been one of the most widely used designs for determining the allocation of attentional resources across multiple tasks, and it has been used successfully with both children and adults (e.g., Coomans et al., 2014; Göthe, Oberauer, & Kliegl, 2007; Irwin-Chase & Burns, 2000). In this procedure, participants must divide their attention between two equally important tasks. Frequently one task is cognitive and the other is motor (e.g., Li, Lindenberger, Freund, & Baltes, 2001; Weerdesteyn, Schillings, van Galen, & Duysens, 2003). Participants may be asked to walk, keep balance, or perform a novel motor task, such as putting with a golf club, while simultaneously counting, tracking a visual stimulus, or performing a memory task (Beilock, Wierenga, & Carr, 2002; Hinton & Vallis, 2015; Pothier, Benguigui, Kulpa, & Chavoix, 2015; see Fig. 2A). Successful performance depends on the ability to divide attention among different sources of information (Maylor & Lavie, 1998). Increased attentional load in a dual-task manipulation elicited increased pupil dilation in healthy young adults, reifying the notion that decrements in performance stem from an overtaxed attentional system and that attentional resources are allocated as a function of effort (Lisi, Bonato, & Zorzi, 2015).

3.1 Childhood

The ability to allocate attention on a dual task increases from ages 5 to 17 years (Sebastian & Hernández-Gil, 2016). The systematic experimental manipulation of large-scale, "whole-body" tasks clearly illustrates cognition–action trade-offs when attention is taxed. For example, 4-, 5-, and 6-year-olds went "grocery shopping like mummy" in a working memory task that asked them to encode the order that an experimenter placed play fruit into a shopping bag. When children responded immediately, they successfully recalled the sequence. However, after the experimenter added a delay without an activity or a delay with the locomotor task of walking to the "grocery store" via a difficult path, children recalled fewer items than in the immediate recall condition, but no difference in performance between these delay conditions. In the unfilled delay, children did not yet have encoding strategies, such as rehearsal, to facilitate later recall. In the delay with a high-demand motor task, impaired

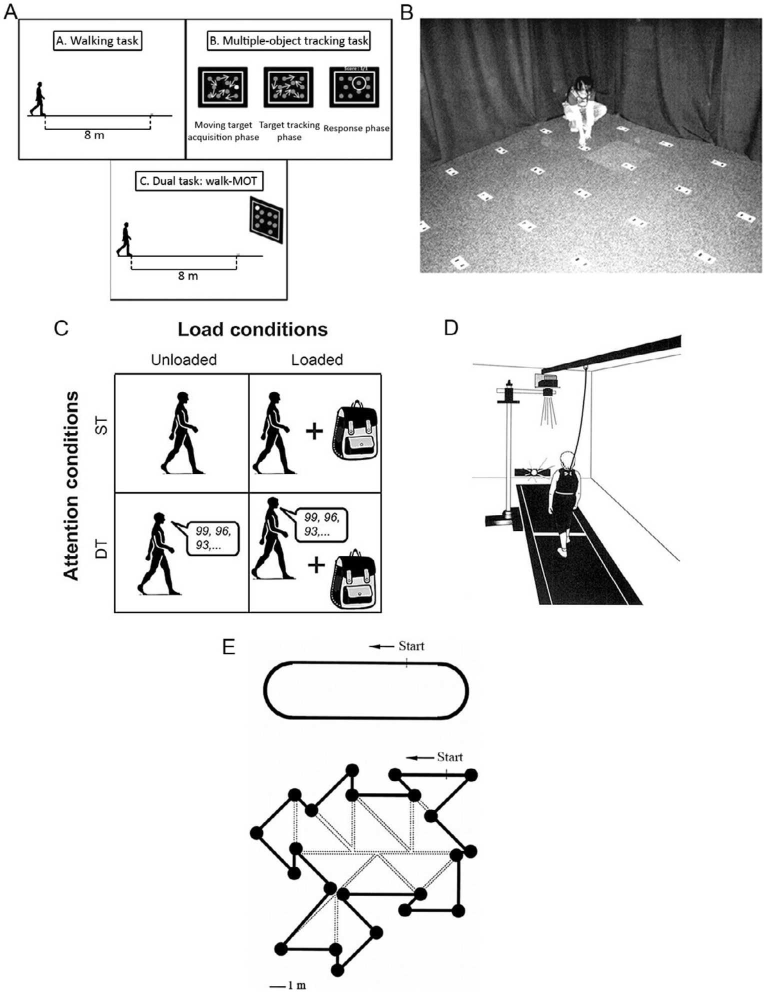

Fig. 2 Illustrations of several dual-task paradigms across age ranges from older children and adults. Those on the right display modified methodologies for young children and infants. (A) Participants walk along a pathway, visually track objects, or complete both tasks simultaneously. (B) Participants search for the lights that change color when the switch is flipped. They must flip the switches manually with either their dominant or nondominant hand. (C) Participants carry a backpack, perform serial subtractions, or complete both tasks simultaneously. (D) Participants walk along a walkway, stepping over projected bands of light, while completing a vocal reaction time task. (E) Schematic drawing of easy or difficult walking tracks participants navigated while recalling a list of words. *Panel (A): Reprinted with permission from Pothier, K., Benguigui, N., Kulpa, R., & Chavoix, C. (2015). Multiple object tracking while walking: Similarities and differences between young, young-old, and old-old adults.* Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 70*(6), 840–849*.

recall was a result of increased attentional demands (Bertrand & Camos, 2015). Interestingly, a delay that included a low-demand motor task improved recall because children's attention was focused on the task at hand, rather than subject to distraction, but not overly taxed. Similarly, 5- to 7-year-olds' strategies for finding a target hidden among a room-sized array became less efficient when the motor demands of the task became more taxing (Smith, Gilchrist, & Hood, 2005; see Fig. 2B). Attentional resources were diverted from spatial working memory to carrying out the motor response which left children unable to organize their search efficiently. Together, these findings suggest that preschoolers' working memory scales as a function of concurrent attentional demands stemming from motor constraints.

Not only are cognition–action trade-offs observed in the context of phylogenetic motor skills (i.e., basic skills typically acquired in the first year of life, including sitting, crawling, and walking) but are also evident with ontogenetic skills. Ontogenetic skills are based more on opportunity or culturally specific training, such as those used in sports (e.g., riding a bike) or writing (e.g., holding a pen). When young children and adolescents completed a digit recall task simultaneous with a paper and pencil tracking task, 5-year-olds showed significantly more costs in completing the tracking task than other age groups. Their performance was partly due to their still-developing fine motor abilities and inexperience manipulating a pencil. Dual-task coordination was scaled to age—even slightly older children (6–8 years) did not show as pronounced costs in the tracking task as their younger counterparts due to their having more opportunity, such as attending school, to practice the skill (Sebastian & Hernández-Gil, 2016).

Cognition–action trade-offs can be elicited over childhood as long as task difficulty continues to tax the maturing attentional system. Similar to preschoolers, 8- to 10-year-olds also demonstrate dual-task motor costs when

Panel (B): Reprinted with permission from Smith, A., Gilchrist, I., & Hood, B. (2005). Children's search behaviour in large-scale space: Developmental components of exploration. Perception, 34*(10), 1221–1229. Panel (C): Reprinted with permission from Beurskens, R., Muehlbauer, T., Grabow, L., Kliegl, R., & Granacher, U. (2016). Effects of backpack carriage on dual-task performance in children during standing and walking.* Journal of Motor Behavior, 21*, 1–9. Panel (D): Reprinted with permission from Chen, H., Schultz, A. B., Ashton-Miller, J. A., Giordani, B., Alexander, Neil B., et al. (1996). Stepping over obstacles: Dividing attention impairs performance of old more than young adult.* The Journals of Gerontology, Series A, 51*(3), 116–122. Panel (E): Reprinted with permission from Lindenberger, U., Marsiske, M., & Baltes, P. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age.* Psychology and Aging, 15*(3), 417–436.*

the cognitive complexity of the task increases accordingly. For example, children's postural sway increased as a function of task difficulty when completing easy or difficult mental math problems, and gait velocity and stride length decreased when simultaneously carrying a backpack and reciting serial subtractions (Beurskens, Muehlbauer, Grabow, Kliegl, & Granacher, 2016; Igarashi, Karashima, & Hoshiyama, 2016; see Fig. 2C). By about 12 years of age children show adult-like dual-task performance: both 12-year-olds and adults prioritized a novel motor task over a simultaneous auditory Stroop task (Hinton & Vallis, 2015).

Interestingly, children's inexperience at strategies for learning can sometimes be advantageous. 8- to 10-year-old children's performance on a task in which they had to learn a perceptual sequence did not differ between single- and dual-task conditions because they focused solely or primarily on the location of a stimulus when counting the number of times the location changed color. In contrast, adults adopted a strategy in which they intentionally integrated perceptual and location sequences. Adults' willingness to devote attentional resources to the cognitive components of a task hindered their performance in the dual-task condition (Coomans et al., 2014).

3.2 Adulthood

By adulthood, the pattern of cognition–action trade-offs reverses from impaired cognitive performance in service of motor performance to impaired motor performance in service of cognitive performance (see Fig. 3A). Young adults become less precise on motor tasks when their attention is divided with a verbal task (Chen et al., 1996; Lamble, Kauranen, Laakso, & Summala, 1999; Weerdesteyn et al., 2003; see Fig. 2D). Motor impairments manifest as greater sway velocity (Maylor, Allison, & Wing, 2001), slower walk times (Pothier et al., 2015), and, given the choice, a preference for using aids to boost cognitive performance over motor performance (Li et al., 2001).

Strength, balance control, and agility decline with age after the third decade of life. As physical capacity declines, risk of injury from poor motor performance increases. When elderly participants are pushed to their limits in tasks with simultaneous working memory or divided attention and motor demands, apparently stable motor performance is revealed to mask instabilities and disruptions to balance control (e.g., de Visser, Pauwels, Duysens, Mulder, & Veth, 1998; Lindenberger, Marsiske, & Baltes, 2000; Maylor et al., 2001). In contrast to young adults, healthy elderly adults show

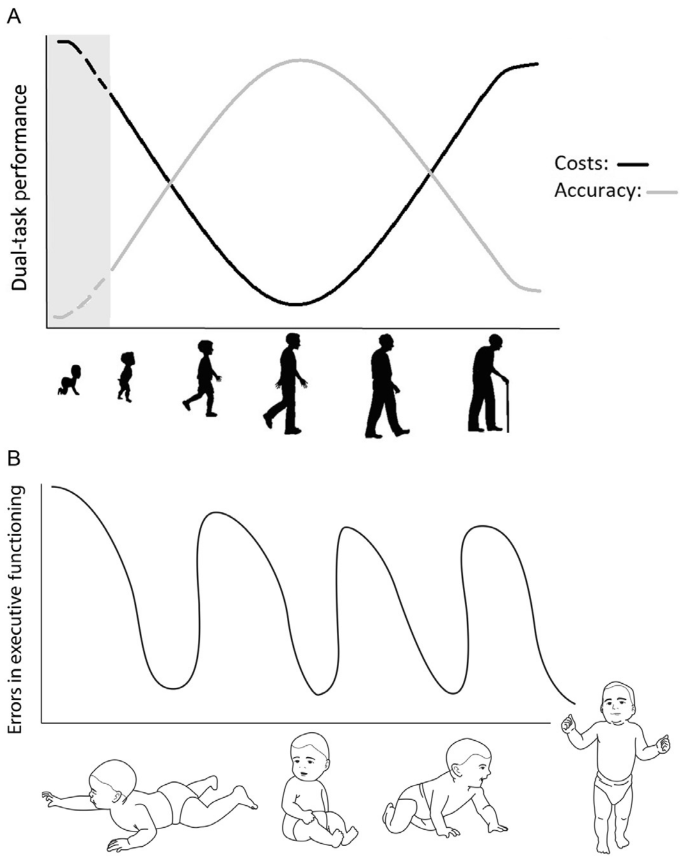

Fig. 3 Graphic depiction of outcomes across the life span for dual-task paradigms. (A) The *x*-axis represents the life stages, from *left* to *right*, of infancy, childhood, adolescence, and young, middle, and older adulthood. The *gray line* indicates costs in either task while trying to perform both at the same time. The *black line* indicates accuracy while performing both tasks simultaneously. The *dashed lines* in infancy depict the expected results if these paradigms could be successfully applied to such a young population. (B) A "zoomed in" look at the *gray-highlighted area* of Fig. 3A. The *shape of the curve* illustrates cognitive errors that fluctuate as a function of motor expertise.

significantly worse performance in the perceptual or cognitive component of a dual task than younger adults, but little to no difference in the motor task (Li et al., 2001; Pothier et al., 2015). Healthy elderly adults' ability to allocate attention during a dual task declines to the level of 9- to 17-year-olds (Sebastian & Hernández-Gil, 2016). During dual tasks, elderly adults allocate attention to preserve their motor performance at the expense of the cognitive demands. For example, when the motor component is made more difficult by making the walking track complicated, older adults were less likely to misstep, but they had significantly worse performance on the simultaneous recall of a word list (Lindenberger et al., 2000; see Fig. 2E). Preservation of motor performance combined with decreasing motor skill leaves fewer resources available for other task components. Thus, effortful cognitive abilities that mature later in development appear to be the first to weaken in old age (Lavie, 2005).

In sum, the developmental trajectory of cognition–action trade-offs appears to follow a u-shaped pattern as young children start out heavily taxed by both cognitive and motor demands. With cognitive maturity and motor mastery in adulthood, the costs of performing dual tasks are minimized until aging brings detriments to physical and mental well-being and, in turn, newfound costs to simultaneously performing multiple tasks. Moreover, the behaviors that are prioritized in a trade-off between cognition and action fluctuate over the life span. In the face of changing bodies and repeatedly going from novice to expert and back again, young children prioritize motor performance, whereas healthy young adults are willing to experience motor decrements as they prioritize cognitive performance. Finally, with potentially serious consequences of motor errors for the elderly, we again observe a shift in priorities whereby motor performance is emphasized over cognition.

3.3 Role of Expertise

Lavie's load theory account of attention predicts that the more effortful a task, the fewer the attentional resources are available to simultaneously perform other tasks (Lavie, 2005). Working memory functions to maintain focused attention on the stimuli that are relevant to the task at hand (Beilock et al., 2002). The simultaneous performance of concurrent executive function tasks results in performance decrements because irrelevant distractors overload working memory, reduce the ability to focus attention on relevant stimuli, and create interference (Lavie, 2005). Novices utilize more attentional resources than experts as they carry out a task because they must hold more task-relevant information in working memory. Expertise brings automatization that frees up attention for skilled performance. The degree of cognitive load can be systematically manipulated by varying levels of expertise and observing the resulting impact on task performance (Beilock et al., 2002). Novices may lack expertise because they are true novices, having had no prior experience with the task or skill, or because their skill is diminished via either experimental manipulation or the aging process.

4. INFANT MODEL OF ATTENTION: EMBODIED COGNITIVE LOAD

Infants' acquisition of multiple new developmental milestones across myriad psychological domains during the first year of life creates a naturally occurring model of changing expertise and effort. Milestone charts in developmental textbooks or pediatricians' offices describe children's first steps and their first words as occurring at the same time, when children are about 1 year of age. However, these estimates are based on group averages, rather than on the developmental timetable of individual children. Anecdotal reports from parents suggest that they perceive their children as acquiring either language or motor skills at a given moment and this is supported by research: attentional resources typically are allocated across domains during development. For example, infants' emotional expressiveness decreases when they begin speaking their first vocabulary words (Bloom & Tinker, 2001). However, when resources are made available in the absence of motor demands, other domains of development get an extra share (Sieratzki & Woll, 2002). Children with spinal muscular atrophy (SMA) show precocious early grammar development and spatial cognition, suggesting that they devote their resources to exploring language and observing the world around them because motor impairments prevent them from exploring "a world they cannot reach" (Oudgenoeg-Paz & Riviere, 2014; Sieratzki & Woll, 2002, p. 423). For children with SMA, language development was more advanced than that of a comparable sample of able-bodied toddlers, and their spatial skills in a manual search task were no different from, or significantly better than, age-matched controls (Rivière & Lécuyer, 2002, 2003). During simultaneous mastery of skill development, competition for attentional resources often manifests in trade-offs. Understanding the nature of these trade-offs can provide insight into the organization and developmental trajectory of attention in infancy and early childhood, or potential compensations in those with disabilities.

One limitation to the typical measurement approaches for studying attention across the life span has been the dual-task method in which participants must understand and carry out a relatively complex set of instructions about consciously allocating their attention so they can simultaneously perform two different tasks to the best of their abilities. Preverbal infants, of course, cannot follow the complex instructions required to attempt the typical dual task employed in these experiments. Thus, there is little systematic study and the resulting depth of understanding of the development and organization of attention in infancy that we have with older children and adults. However, a domain in which infants can provide behavioral data sets as comprehensive as those provided by older children is motor development (Adolph & Berger, 2011). Given the importance of changing motor expertise over the course of adulthood for our understanding of the organization of attention, the developmental trajectory of dual-task performance has implications for predicting cognition–action trade-offs related to the allocation of attention in infants. Thus, the goal of this section is to synthesize disparate, illustrative examples in the literature and ultimately arrive at a cohesive embodied cognitive-load model of attention in infancy.

From an embodied cognitive-load account, "physically executing… effortful or complicated body movements can impose a cognitive load" (Warburton, Wilson, Lynch, & Cuykendall, 2013, p. 2). Conversely, reducing the amount of movement, minimizing the scope of movement, or providing external support to movement can yield cognitive benefits. This perspective would predict that infants at the cusp of acquiring a new motor skill would show patterns of behavior akin to those of the elderly, where motor errors could have severe consequences, rather than healthy young adults who can afford to risk motor errors. Possibly the earliest evidence for this phenomenon has been observed in 3-month-old infants' movement–attention coupling (Robertson & Johnson, 2009). In this study, infants' baseline level of body movement decreased at the onset of looking, suggesting that movement is suppressed to decrease load that frees sufficient resources for visual attention.

The study of attention in preverbal infants who cannot follow complex instructions or execute most of the tasks that typically comprise dual-task conditions (visuospatial memory, arithmetic, keyboard press, etc.) requires alternative paradigms. For young infants, age-appropriate, single tasks that include components from different developmental domains, especially big, observable, motor behaviors, have been most promising to date. Given that young infants have limited attentional resources, tasks that require extra effort on one aspect would siphon processing resources from another aspect of the task (Boudreau & Bushnell, 2000).

4.1 Sitting and Reaching

Even after infants begin attempts to independently sit upright, there is still a protracted period of development as sitting becomes increasingly stable

(Harbourne & Stergiou, 2003). Novice sitters become expert sitters by discovering more stable and regular strategies for keeping balance and by exploring variations in sitting to home in on the most appropriate and functional sitting strategies (Harbourne, Giuliani, & MacNeela, 1993). Sitting posture changes in the context of other rapidly emerging changes in body growth and motor skills, such as reaching. As infants become more successful at reaching for varying objects in multiple locations, prospective postural control in sitting emerges (Harbourne et al., 2013). To obtain an object, infants may sacrifice sitting stability and tip over, only to reach again immediately if returned to a sitting posture by a parent. Even if falling does not occur, the posture of newly sitting infants when reaching is destabilized as attention shifts. After a few weeks, when infants' sitting skill improves and many reaches have been experienced, sitting destabilization diminishes. This trade-off of resources between sitting stability and reaching is not merely a matter of strength or reaching practice. When nonindependent sitters are provided external postural stabilization, reaching appears as skillful as seen in an independent sitter, indicating that when infants do not need to allocate resources to both tasks (posture and reach), the remaining task can be accomplished successfully. Thus, the persistence and attention allocated to obtaining and manipulating an object in the newly gained upright position of sitting reduce the attentional resources needed to maintain sitting.

This exemplar developmental trajectory through the emergence of sitting and an additional task, including a cognitive task, allows for the comparison of novices and experts in the same posture performing the same task. An embodied cognitive-load account would predict that novice sitters would require more attentional resources to keep balance than expert sitters, or perform a simultaneous task in an immature way. Indeed, in studies comparing cognitive load during the emergence of sitting (Cashon, Ha, Allen, & Barna, 2013; Harbourne et al., 2014), infants perform a visual task in an immature way during the emergence of sitting. Infant looking time serves as an indicator of information processing, such that longer looks at objects, particularly novel objects compared to familiar ones, are typical in very young infants. During the first year of life, infant looks become progressively shorter as they begin to recognize familiar objects and process information more quickly (Bornstein, 1998). However, infants who are learning to sit, regardless of age, exhibit longer looking times than infants who are skillful sitters (Harbourne et al., 2014). In another paradigm where age was controlled as a predictor, infants who were learning to sit showed a lack of holistic face processing, a skill that infants possessed prior to learning to sit, and that skill reemerged once they achieved sitting independence (Cashon et al., 2013). In these cases, infants could not perform the cognitive task when working to balance in the newly upright sitting position, and they required more time for cognitive processing during the newly emerging posture.

Goal-directed reaching takes months to mature and coincides and interacts with developing a sitting posture. At around 4 months of age, infants' reaches lack the control and direction of mature reaches. Immature reaches jerkily change the direction as infants move their hand toward the goal. These direction shifts are termed "movement units" and are defined by one acceleration and deceleration (von Hofsten, 1980). A mature reach generally includes only one or two movement units. However, immature reachers correct and overcorrect an average of four times before they contact the goal. In comparison, by the time infants are 7 months old, their reaches are adult-like, typically containing only two movement units (von Hofsten, 1993; von Hofsten & Ronnqvist, 1993).

The protracted achievement of reaching skill provides another example where we might expect a competition between cognition and action. To test this, Boudreau and Bushnell (2000) systematically isolated attentional demands of motor and cognitive load in a two-part reaching study designed to be as closely analogous to a dual-task adult study as could reasonably be done with infants. In the first part, motor demands were experimentally manipulated, while cognitive demands were held constant. Nine-and-a-half-month-old infants either had to reach precisely or could reach "sloppily" to activate a lever in a perceptual discrimination task. Infants in the more demanding motor condition showed compromised discrimination learning compared to the infants in the less demanding motor condition, suggesting that attentional resources were diverted from the cognitive goal to the more immediate requirements of motor planning and execution. In the second part of the study, cognitive demands were manipulated, while motor demands were held constant. In this task, 10.5-month-old infants had to retrieve an out-of-reach toy by pulling on a cord attached to a tray holding the toy. The number of steps in the problem before getting to the toy varied from one step (toy directly on the tray) to three steps (toy on the tray with two covers that had to be removed). The assumption was that "subgoaling" the three steps was more cognitively demanding because the components of the problem had to be coordinated, and the relation of the subgoals to each other had to be maintained. Behavioral trade-offs were again observed with motor planning becoming slower as the number of steps in the means-ends problem increased. In this case, attentional resources were diverted from motor planning to manage the cognitive demands. Thus, in both parts of the study, the focus of attention shifted depending on the goals of the task and regardless of whether the cognitive or motor component was the taxing factor. These findings provide further evidence that cognitive and motor demands compete for a shared pool of limited attentional resources and that competition results in cognition–action trade-offs.

4.2 Independent Locomotion

With the ongoing acquisition of new motor skills over the first year of life, infants repeatedly transition from novice to expert (see Fig. 3B). Soon after they have mastered sitting and can successfully keep balance while engaging in other tasks, they begin acquiring independent locomotion. They are novices all over again and must learn to keep balance in this new posture (Adolph, 2000). Outside of the laboratory changes are taking place in multiple developmental domains at the same time. On average infants start to crawl at around 6 months of age (Adolph, Vereijken, & Denny, 1998). At the same time, they also start babbling and engaging in intentional vocalizations (Iverson, 2010). The embodied cognitive-load account would predict that individual infants would be unlikely to have sufficient attentional resources to devote to multiple effortful tasks.

We studied how infants manage the efforts of coping with multiple "in the moment" demands as more than one skill is acquired simultaneously. Berger, Cunsolo, Ali, and Iverson (2017) documented the developmental trajectory of infants' vocalizations around the transition to crawling and pulling-to-stand. In a longitudinal, naturalistic study, infants were observed playing at home every 2 weeks from 2 weeks prior to when they first started crawling until 4 weeks after crawling onset. From videotapes of each session, all postures and vocalizations were exhaustively coded. Odds ratios of the likelihood that a given posture and vocalization would occur simultaneously in real time revealed that vocalization was unlikely to co-occur at the onset of crawling (see Table 1, session 2) and pulling-to-stand (see Table 1, session 3), but equally likely to co-occur after a month of crawling experience (see Table 1, session 4). These values can be interpreted as the odds of infants vocalizing while crawling during the first session where they ever crawled are 13–100, but are not significantly different from even by the time they have

Table 1 Mean Odds Ratio Values at Each Session

Session	1	2	3	4
Crawling	NA	0.13 ($n=13$)**	0.54 ($n=16$)*	1.33 ($n=22$)
Sitting	1.24 ($n=15$)	1.87 ($n=18$)	1.21 ($n=17$)	1.92 ($n=22$)
Standing with support	0.54 ($n=8$)	1.26 ($n=12$)	2.14 ($n=12$)*	1.62 ($n=20$)
Pulling-to-stand	NA	0.10 ($n=3$)*	0.05 ($n=6$)**	0.45 ($n=10$)

P values reflect significance testing against 1.
*$P \leq 0.01$; **$P \leq 0.001$.

been crawling for 4 weeks. Infants' allocation of attention over the transition to crawling and pulling-to-stand prompted behavioral trade-offs. During mastery of a novel skill, infants may have had difficulty allocating attention across multiple domains, but with newfound expertise, a decrease in attentional load for the new skill facilitated simultaneous behavior in other domains.

4.3 Inhibition

In the classic, Piagetian A-not-B task, an experimenter hides a toy at one location and infants manually search for it. After several trials, the experimenter hides the toy at a new location, in full view of the infant, and again the infant searches. Infants younger than 12 months of age often make the "A-not-B error," an error of inhibition in which they reach back to the original location (A), despite observing the hiding of the toy at the current location (B) (Diamond, Prevor, Callender, & Druin, 1997). Piaget's (1954) A-not-B task was originally intended to test infants' object permanence, but several recent replications and expansions have challenged the construct validity of that interpretation (e.g., Diamond et al., 2005). The current view is that success on the A-not-B task depends on infants' ability to inhibit a prepotent response. Inhibition is a key executive function necessary for cognitive control (Blackwell, Chatham, Wiseheart, & Munakata, 2014) and, as repeatedly demonstrated in the adult literature, is attentionally taxing. Thus, this section explores the relation between infants' ability to inhibit and attentional demands, particularly those that relate to motor proficiency as new skills come on-line, and expertise is attained or experimental manipulation changes task demands.

4.3.1 Inhibition and Attentional Demands

In a visual A-not-B search task, 10- and 12-month-olds watched a sequence of movies in which a target disappeared and reappeared repeatedly behind one occluder and then disappeared and reappeared behind another occluder (Watanabe, Forssman, Green, Bohlin, & Von Hofsten, 2012). Half of the infants experienced a distractor during the B trial. An eye tracker documented infants' anticipatory looking—where did infants expect the target to reappear? An inability to inhibit would mean that infants would look to the original occluder where they had already seen the target several times even after it disappeared behind the new occluder. Infants in the distractor condition had more difficulty inhibiting their looks to the original location than infants in the regular condition. As predicted by the embodied cognitive-load account, visually attending to the distractor taxed attentional resources such that infants could not also inhibit their anticipatory looks simultaneously.

A series of locomotor A-not-B tasks directly tested the role of locomotor expertise on infants' ability to inhibit. This design is one of the closest approximations to a dual task that we can use with infants because the locomotor A-not-B task comprises components from different developmental domains that are inextricable when carrying out the task. In one version of this task, crawling and walking infants, all of whom were 13 months old, had to reach a caregiver who was waiting for them at the far end of a pathway (Berger, 2010; see Fig. 4A). After several trials, the caregiver moved to the end of a different path and infants chose which one to take. In this case an inability to inhibit would mean that infants would take the old, familiar path and detour around to the caregiver waiting at the end of the new path (see Fig. 4B). Infants who could inhibit would take the new path directly to the goal. All of the infants were the same age, but those who were still crawling were experts in their posture because they had several months of crawling experience, whereas walkers were novices with an average of no more than a month of walking experience.

Neither group perseverated after the caregiver switched locations in a low-demand condition in which infants simply had to walk on flat ground. In contrast, in a high-demand condition where infants had to navigate their way through a 5-ft. long, chest-high tunnel to reach the caregiver, walking infants were more likely to perseverate than crawlers. Other frequent errors observed in the tunnel condition were mismatches between infants' bodies and the tunnel, such as standing up too early or bumping their heads upon entry (see Fig. 4C). In addition to inhibiting

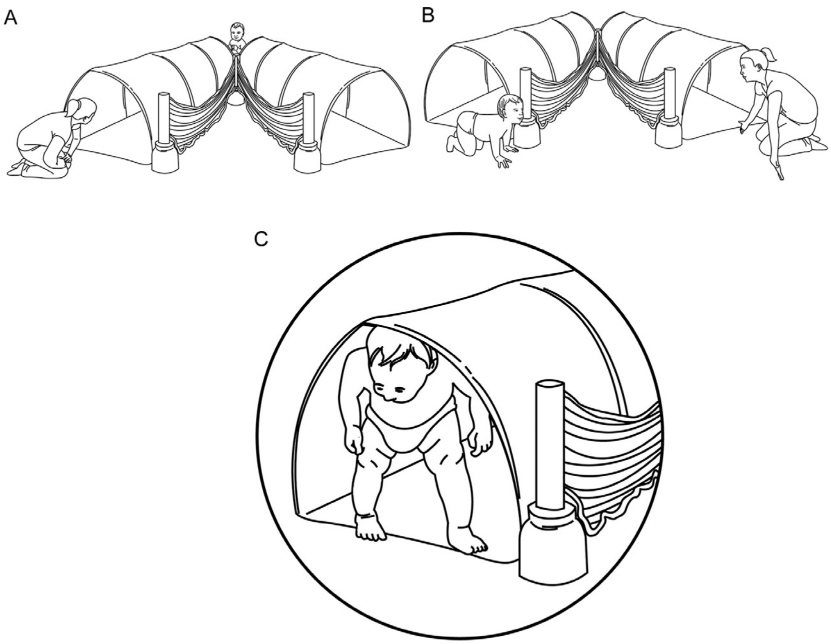

Fig. 4 In the locomotor A-not-B task, (A) infants started each trial at the entrance to two possible pathways. Caregivers at the far end of one of the tunnels encouraged infants to take the direct path to them. (B) On the B trial, caregivers move to the end of the other pathway. Infants who perseverated took the A path to the end and had to detour around to reach the caregiver at B. One reason the tunnel task is so taxing for new walkers is that they must choose an alternative method, like crawling, to fit their bodies through the tunnel. (C) Instead, they have trouble inhibiting their primary locomotor method of walking, even though it may mean a mismatch between body and tunnel. *Line drawings by Ricardo Solis/Costa RicART.*

taking the familiar path, walking infants also had to inhibit using their typical locomotor strategy, devise an alternative to fit their bodies through the tunnel, and maintain that strategy for the length of the tunnel. In accordance with the embodied cognitive-load account, the greater the motor demands, whether via task manipulation or locomotor experience, the greater the cognitive error. Novices likely prioritized the motor demands of the task due to the risks associated with losing balance control that left them unable to attend, plan, inhibit, and keep the effective locomotor strategy active in working memory. In contrast, crawlers' motor expertise allowed them to devote the attentional resources needed for executive functioning.

In an earlier version of the locomotor A-not-B task in which age was held constant, but task difficulty was experimentally manipulated, 13-month-old walking infants showed a similar pattern of cognition–action trade-offs (Berger, 2004). The same infants who easily inhibited on the "B" trial in a low motor demand condition requiring only walking on flat ground had difficulty inhibiting in a high motor demand condition that required them to descend a set of stairs to reach a caregiver waiting at the bottom. A close examination of infants' strategy choices on the "A" trials provided additional insight into the organization of attentional resources. Infants who backed or scooted down the stairs or who held onto the experimenter or banister for support were less likely to perseverate than infants who walked down the stairs. The alternative locomotor strategies made stair descent biomechanically easier, reduced motor demands, and, in turn, minimized the attentional load.

4.4 Problem Solving

Variability in a sample has traditionally been treated as noise in the data or a nuisance to be dealt with during data analysis. Siegler's "overlapping waves theory" of the development of problem solving and strategy use was a breakthrough in the field of cognitive development in part for embracing within-child variability (e.g., Lemaire & Siegler, 1995; Siegler, 1996, 2007). From this account, variability is used as a tool for understanding the underlying causes of how children choose and execute strategies for solving problems (Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Based on Siegler's ideas, densely timed observations of preschoolers choosing the most appropriate tool for retrieving an out-of-reach object or school-aged children solving arithmetic problems revealed that the development of problem solving starts with the acquisition of new strategies, continues as novices map prior experiences to novel tasks, and culminates with increasing expertise in the newly attained strategies (see Siegler, 2004, for a review).

Researchers face similar methodological limitations to the study of the development of problem solving in infancy as described previously in the discussion of the dual-task literature: traditional approaches for studying strategy choice and problem solving have emphasized verbal and mathematical problems that are inappropriate for use with infants. Thus, the study of problem solving in infancy has only recently delved into a microgenetic level of detail akin to those used with older children with the invention of designs that capitalize on infants' rich motor behavior, making problem solving "observable."

One such design is depicted in a recent study of the development of problem-solving strategies in infancy, in which Berger, Chin, Basra, and Kim (2015) observed novices and experts devise real-time solutions to the problem of descending stairs. Stair descent requires generating a goal of reaching a parent at the bottom of the staircase, coordinating the steps necessary to get there, possibly devising alternative strategies, sustaining effective strategies, and maintaining balance—all tax attentional resources (Carrico, 2013; Woollacott & Shumway-Cook, 2002). 13- and 18-month-olds descended a wooden, five-step staircase, with custom-built low (infant-sized) handrails five consecutive times in the laboratory. Their spontaneous stair descent strategy choices were coded from the video. This yielded a high-density sample so that we could capture change within and between descent trials. All infants used multiple strategies to descend the stairs (walking, backing, or scooting down on their bottoms), generally within a single trial from step to step. Most 13-month-old novices started out walking down the staircase, but over the course of a trial the proportion of infants walking down increased from around 60% on the first step to around 75% by the time they got down to the last step. In contrast, around half of the 18-month-old experts, who had almost twice as much stair descent experience as the 13-month-olds, started walking down the staircase, but were more likely to switch to scooting with each step. Both groups repeated their respective patterns at the start of each trial as if being placed at the top of the staircase was equivalent to the start of an entirely new problem. Choosing to walk meant that the novice 13-month-olds were pushed to their physical limits and often had to be rescued by the experimenter when they started to fall. Scooting, however, lowers the center of mass, leading to a more stable descent choice. Further, the older infants were over 1.5 times as likely to augment their balance by grabbing a handrail than the younger infants.

These patterns provide rare insight into the role of attention on the development of problem-solving skills in infancy. With each new trial novices appeared to consider the various possible strategies, but the combined motor demands of stair descent and the cognitive demands of weighing alternative strategies taxed attentional resources to the point that they could not inhibit a familiar strategy. Experts with more motor experience more easily considered alternative strategies and maintained those solutions over the course of the trial. The mechanism for transitioning from inefficient to successful strategies was the automatization that comes with experience. As attentional resources that previously had been allocated to executing an action or coordinating multiple steps of a motor plan are freed up, they can be reallocated to make problem solving more efficient (Siegler, 2000). Practice increases familiarity with a problem, which, in turn, allows working memory resources to be reallocated to the exploration of alternative strategies (Shrager & Siegler, 1998).

In contrast to holding the task constant and allowing motor expertise to vary, an alternative approach to studying the role of attentional load in problem solving is to hold age constant and experimentally manipulate task difficulty. Carrico (2013) took the latter approach by asking 2-year-olds to solve a multistep problem that varied in difficulty. The primary task taxed working memory by asking children to find a hidden food lure. To make the problem more difficult, another step was added that introduced a motor component. This step varied in difficulty from simply observing the experimenter opening the latch of a cover to access the search task, to receiving training on how to work the latch, to having to solve the latch step without any training.

The addition of the second step in the problem taxed the 2-year-olds' attention to the extent that search performance was impaired in all conditions. Prior to adding the latch task, attention was already allocated toward keeping a goal in working memory, sequencing the requisite steps for obtaining the goal, and continually updating working memory as to the status of the search task. Adding a motor subgoal to the problem prompted a cognition–action trade-off in the form of search inefficiencies (Carrico, 2013).

In sum, observable action and movement are not merely opportunities for gaining purchase on infant development. Embodied cognition means that there can be no true insight into attention without understanding sensorimotor activity as a context for expertise, a source of attentional demands, or the result of a decision to act (e.g., Smith & Gasser, 2005; Thelen, 2000).

5. IMPLICATIONS FOR COGNITION IN ACTION

5.1 Mechanisms of Development Change

As a body of work these studies have implications for models of infant development that use age as a parameter. The many instances in which age was independent of behavior show that age is frequently a proxy for other explanatory mechanisms. For many of the examples in this chapter, skill and experience were implicated as factors associated with age, but which may have more explanatory power as mechanisms underlying development.

That attentional resources must be devoted to a task demand is inextricably linked to infants' proficiency at the skill required to meet that demand—any skill at which the child is a novice has the potential to add to task difficulty. Due to infants' constantly fluctuating abilities in multiple developmental domains, the definition of increased task demands must also constantly change. In the motor domain, when infants can use an experienced locomotor skill (i.e., crawling, scooting) to reach a goal, descend a staircase, or navigate a tunnel, they are better at devising alternative strategies, coordinating subgoals of a complex plan, and keeping solutions in mind than infants who use a new, inexperienced skill (i.e., sitting, walking). For example, infants who successfully reached around a transparent barrier took months to solve the problem of detouring when they had to use their less experienced method of crawling (Lockman, 1984).

5.2 Gradual Nature of Development

These studies also serve to illustrate the gradual nature of development, as opposed to characterizing skill acquisition as dichotomous or all-or-nothing. Methods of assessment may shape the way we conceptualize developmental trajectories. Given the rapid and dramatic change that occurs over the first few years of life, tools for documenting behavior must be able to capture developmental processes, but standard measures of inhibition have largely been dichotomous and have tended to neglect behavioral variability. For example, in the Dimension Change Card Sort Task, a traditional test of preschoolers' ability to inhibit, preschoolers are typically classified as either being able or unable to inhibit based on which rule they used to sort cards after the rule they had just been using changed (e.g., Zelazo, 2005). However, in a version of the DCCS task that adopted richer behavioral coding schemes, such as self-corrections and verbal responses, performance was more variable and wide ranging than the standard design portrayed (Kirkman & Berger, 2013). Behavioral outcomes are constrained by the structure of the research design which, in turn, shapes interpretation. In this chapter, we emphasized the insight that is gained into patterns of development when observable motor behaviors are carefully documented. Across studies, infants showed a gradual increase in capacity for performing higher-level cognitive processes that could only be captured by allowing them to express the full range of their abilities.

5.3 Interaction Between Developmental Domains

Development in different psychological domains (i.e., language, motor, cognition) occurs simultaneously, especially during infancy, but developmental research has traditionally been segmented for ease of experimental design and conceptualization. When multiple domains are studied together, it is typically in the context of how they complement each other. To reflect the reality that psychological domains do not develop in isolation, recent research has explicitly attempted to "put the baby back together" by examining the developmental interaction among different domains.

In many of the examples in this chapter, infants' success on a given task can be predicted only by accounting for both their cognitive and motor abilities. The implications go beyond just cognitive or motor development, however. These studies are prime examples of the utility in studying traditionally disparate domains of development, particularly with an emphasis on studying how different developmental domains interact with each other in the face of simultaneous change, rather than studying them in isolation.

5.4 Motor Tasks as a Model for Understanding Development

There are striking parallels between infants' behavior in motor and locomotor problem-solving tasks and older children's behavior in more classic cognitive tasks. By making the process of allocation of attention observable, motor tasks can serve as a model for understanding development in infancy. For example, the timing and order of milestone acquisition is notoriously variable. Examining the pattern of trade-offs in the acquisition of developmental milestones on multiple timescales as infants concentrate on one effortful behavior at a time may help to explain some of that natural variability. Documenting strategy use and decision making in very young, primarily preverbal, children has the advantage of providing insight into a population that is otherwise unable to comment on its own actions.

Early in the achievement of a new motor task infants appear to discover the strategy of stabilization, or "freezing the degrees of freedom" of the body, to allow resource allocation or redistribution of attention to another area. For example, newly standing infants, despite being generally unbalanced in standing, will exhibit less body sway to perform a goal-directed task with a toy (Claxton, Haddad, Ponto, Ryu, & Newcomer, 2013). This strategy of increasing stability continues throughout development and into adulthood, as a healthy sharing of resources when cognitive demands exist during a typical postural task such as standing (Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003). Given the three types of attentional systems described at the beginning of this chapter, the strategy of stabilizing or freezing the body segments when performing a cognitive task may reflect a natural cooperation between the orienting system of attention and the executive system. Once children attain stability in a new posture, such as standing, the orientation of the body should not require constant vigilance, permitting a greater focus of attention to another area.

6. IMPLICATIONS OF COGNITION–ACTION TRADE-OFFS FOR MOTOR DELAYED AND IMPAIRED INFANTS

The evidence for cognition–action trade-offs during infancy suggests a set of principles for understanding delayed development which could contribute to the enhancement of core features of early intervention. Traditionally, the motor and cognitive systems have been viewed as separate through multiple lenses including developmental stages of progression, standardized testing, neurologic function, and skilled performance. Despite the historic tradition in medicine and education of attempting to separate the motor system from cognition, the two systems are bound together.

At the most basic level early motor deficits block successful performance of simple cognitive assessment items. For example, an early cognitive test item (5 months) on the Bayley III infant cognitive test is to observe whether the infant can transfer an object from one hand to the other. A 5-month motor test item on the same test (Bayley III) entices the infant to attempt to pick up a small pill-sized object. Clearly, these two test items involve both motor skill (orienting head, eyes, and hands to an object, reaching accurately, controlling posture while moving the limbs) and cognitive skill (perceiving that an object is "graspable," deciding the object is within a distance to obtain, being interested in exploring the object in the environment, planning what type of grasp to use). Early in life, tests for cognition are strongly motor based, making it difficult to diagnose delays in one system vs another. Standardized assessments such as the Bayley III that focus on the discrete *performance* of tasks do not consistently identify or classify delays in the first 2 years of life and provide poor prediction of future cognition relative to assessments that involve perceptual-motor exploration and problem solving (Lobo & Galloway, 2013; Lobo, Paul, Mackley, Maher, & Galloway, 2014). Tests for cognitive skill in infancy that are motor dependent do not help determine which system is deficient and act to perpetuate the division between motor and cognitive domains in early life

(Visser, Ruiter, van der Meulen, Ruijssenaars, & Timmerman, 2014). Thus, the interdependence of motor and cognitive systems, and interrelated delays can cause a cascade of overall developmental problems. Current infant tests are now beginning to recognize the overlap of test items for motor and cognitive domains and attempts are being made to accommodate for motor deficits (Visser, Ruiter, Van der Meulen, Ruijssenaars, & Timmerman, 2013). However, the concept of a cognition–action trade-off has rarely been addressed as a factor in early intervention, and the allocation of attention is rarely considered (Lobo, Harbourne, Dusing, & McCoy, 2013). As noted in the many examples provided from typical development, individual differences and atypical strategies of the cognition–action interaction may contribute to an overall change in the trajectory of a child's functional skills.

7. EVIDENCE FROM ATYPICAL POPULATIONS

In the event of atypical early development, either due to prematurity or damage to vulnerable systems, how might the cognition–action trade-off be affected? In typical development, we described the cyclical and repetitive nature of resource allocation as motor and cognitive skills emerge. The flexible allocation of resources serves skill advancement by directing attention to important features of the task and subsequent adaptation. But what happens if there is increased effort required in one system, such as the motor system, in the case of a child with a movement delay or disorder? Do strategies of resource allocation differ in atypical development? First we discuss evidence from studies of infants, followed by evidence from older children.

7.1 Infants

Typically developing infants exhibit variability in movement patterns that allows for the selection of the most suitable strategy for a given function or task, or a set of individual characteristics. Typically developing infants are notoriously "wiggly." An absence of this quality of continuous and variable movement provides diagnosticians and interventionists with a reliable and valid means of early diagnosis for a movement disorder (Einspieler & Prechtl, 2005). Infants with potential developmental movement disorders exhibit less variable movement and a poverty of motor strategies (Hadders-Algra, 2004). Limitations in motor strategies may contribute to differences in the allocation of resources for motor and cognitive tasks. Very early difficulties in movement could lead in different directions: (1) the child needing to allocate a large proportion of resources toward movement efforts, with a deficit of attention to cognitive exploration; or (2) an emphasis on cognitive areas with less allocation of attention to movement, resulting in a lack of experiences and exploration that cascades to future deficits in both motor and cognitive areas.

A cognition–action trade-off as sitting emerges is particularly significant for children with early delays in motor milestone attainment since the attention required for a difficult motor task may come at the expense of cognitive efforts. Berger, Harbourne, and Lliguichuzhca (2017) compared early sitting skills in infants with typical development, infants who were premature, and infants with or at risk for cerebral palsy (CP). While they played with toys in the newly acquired sitting position, infants' postural adjustments during times of focused attention were analyzed. Typically developing infants and infants at risk for CP made fewer trunk movements during periods of focused attention than nonfocused attention, a strategy of "stilling the body" seen at older ages and in other postures. Preterm infants exhibited more trunk movement than infants in the other groups and their trunk movement did not differ based on attention type. At this stage of motor development the capacity to minimize extraneous movements or "sitting still" may allow infants to allocate resources to be prioritized for attention to the task at hand, similar to older children and adults in the standing position. Conversely, the ability to "still" the body's extraneous movements may be akin to the disengagement of attention from one system (the orienting system of attention that requires constant updating of information to maintain posture) to allow the reallocation of resources to focus attention on the manipulation of an object and cognitive function related to that object. Premature infants' excessive trunk movement that did not adapt to task requirements could, in the long term, impact tasks requiring attentional resources. In a previous study, infants with CP and resulting delays in achieving sitting (mean age = 21 months) showed increased focused attention to objects as they achieved independent sitting, possibly due to the greater ability to stabilize the body allowing more resources for attention (Surkar, Edelbrock, Stergiou, Berger, & Harbourne, 2015). Focused attention is the duration of concentrated examination of objects during independent play and object exploration (Ruff, Capozzoli, & Saltarelli, 1996) and is most likely akin to the executive attention system. However, as some of these infants became mobile, long periods of focused attention to objects decreased (Surkar et al., 2015). From a resource allocation account, the new motor skill of crawling would temporarily disrupt the cognitive concentration for focused attention. In another experiment, infants with motor delays tended to look longer at objects than their typical counterparts during sitting development (Harbourne et al., 2014). These longer looks are thought to reflect the need for longer processing time to pick up information while allocating attention to the difficult task of maintaining the newly attained vertical position. This may also reflect an inability to disengage from the orienting system of attention and shift resources to the executive system. During the emergence of postural control in sitting, infants with motor deficits may experience an additional load to the cognitive system as limited attentional resources are allocated to the motor activity of maintaining an upright posture. Conversely, if cognitive engagement is prioritized, posture may suffer by disallowing the monitoring necessary to maintain verticality if a challenge to balance occurs.

From the resource allocation perspective, infants who either have or are at high risk for developmental delays would likely need more time for each area—cognitive and motor—whether their diagnosis implicated the motor system. In fact, infants with established motor delays explore less very early in life, and their exploratory behaviors are less variable, with fewer combinations of behaviors and fewer multisensory behaviors than typically developing infants. Furthermore, high-risk infants tend to perform generic behaviors on objects rather than matching their behaviors to object properties, thus missing information about the unique properties of objects (Lobo, Kokkoni, Cunha, & Galloway, 2015). Hypothetically, the motor demands of each developmental milestone and task, or the inability to modify or stabilize a posture, could tax attentional resources and slow cognitive processing.

Infants who are preterm display delayed adaptive postural control quite early in life, resulting in delays interacting with objects even prior to sitting (Dusing, 2016). Movement control that is effortful in the first few months of life may predispose children to difficulties in smoothly adapting the attentional system to key information from the start of development. Children who were very preterm (<30 weeks) notably continued to display deficits in postural control as they grew, with 4-year-old children showing a longer center of pressure path at the base of support (more postural adjustments with larger excursions) during both dynamic and static standing than their typically developing peers, particularly during a concurrent cognitive task (Lorefice et al., 2015). Very preterm children, although not necessarily identified with an overt motor deficit in the early years, have a higher chance of exhibiting difficulties at school age (Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009). Thus, it appears that solving cognitive and motor problems requires attentional resources that contribute to the success of the action and outcome, all of which is dependent on previous skill building and resource sharing within an environmental context.

7.2 Older Children

For children with a movement disorder, such as CP, a variety of motor deficits may limit the possible strategies for resource allocation. However, some evidence indicates that children with CP adapt in the same way and by using similar strategies as typically developing children, despite differences in the patterns of movements used. For example, Schmit, Riley, Cummins-Sebree, Schmitt, and Shockley (2016) observed cognitive benefits stemming from movement reduction in children between the ages of 5 and 12 years, half with CP and half typically developing, as they engaged in a functional play task. Participants' pretended to take the temperature of a stuffed animal by keeping the thermometer precisely in the center of the animal's mouth without touching the sides. Task difficulty varied as a function of the size of the animal's mouth. Despite greater postural variability and irregularity by the children with CP at baseline, children in both groups stabilized their body to reduce their movement during the functional precision task. Reaching per se is not sufficient to reduce trunk sway; functional reaching tasks generally elicit postural destabilization, suggesting that the reduction in movement is not solely to provide a stable base for the arm (Liu, Zaino, & McCoy, 2007). Thus, whether implicit or explicit, stilling the body frees up attentional resources for solving problems within a functional motor task across age, context, and motor ability.

7.2.1 Motor Deficits

On the other hand, the allocation of resources using a strategy created during typical development may be blocked or altered when motor deficits exist. Typically, children discover an efficient movement strategy, over time and with errors, that accomplishes a given goal, such as retrieving food through an aperture, with the least energy expenditure (Achard & von Hofsten, 2002). An example of such a strategy for an older child would be picking up a tool, such as a spoon, by planning a smooth approach to the handle, and positioning the hand to grasp the handle in the grip that is needed for using the bowl to scoop and deliver the food to the mouth (comfortable end state position) (Keen, 2011). However, children with hemiplegic CP did not adapt the movement so that their manipulation of an object would be in a comfortable position for the end of the task

(Crajé, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010), indicating a potential dysfunction between resource allocation and the action and planning (cognitive) systems. This lack of planning the movement or adapting to the task exists even when the body part being used is not specifically affected by the CP, as in the nonhemiplegic arm (Chen & Yang, 2007). The possibility remains that children with hemiplegia who use a movement pattern that appears inefficient to the observer may be using a compensatory pattern that allows resource allocation suitable to their own unique set of resources and skills. Movement patterns seen in typical development may reflect a common problem solution for developing human anthropometrics that differs from the structures and strengths in children with variable muscle control and tightness.

Motor impairments of different types or severities may interact in varying ways with cognition and have different outcomes for a cognition–action trade-off. Children with a poverty of movement may lack exploration and the ability to orient to the environment, contributing to a reduction in cognitive advancement due to general problems with picking up information. High-risk infants with a lack of variability in movement tend to perform generic behaviors on objects rather than matching their behaviors to object properties, thus missing information about the unique properties of objects (Lobo et al., 2015). On the other hand, children with too much variability in movement, such as children with a cerebellar disorder, may present with an inability to still the body to keep attention focused, or lack the ability to maintain visual attention as needed to pick up important information (Tavano et al., 2007).

On the surface, developmental coordination disorder (DCD) appears to be less challenging than some other diagnoses, such as CP. DCD is defined by performance in daily motor coordination activities that is substantially below that expected given the person's chronological age and measured intelligence. The difficulties of children with DCD are often not apparent until ontogenetic skills are demanded, such as learning to ride a bike; thus, DCD is usually diagnosed at school age. Given this definition of the disorder, we expect that motor tasks would strain the attentional system and resource allocation would be different in individuals with DCD vs other atypical groups. Cognitive and motor difficulties during dual-task activities are common in this group of children (Schott, El-Rajab, & Klotzbier, 2016). Fine motor difficulties are more common than gross motor in children with DCD, but both types of motor activity tend to suffer errors during a concurrently challenging cognitive task over and above that of the activity of typically developing children. Children with DCD appear to preferentially allocate attention to the cognitive focus of a task and sacrifice the motor control component, possibly because the cognitive area is less energy consuming or because the attention required for the motor task is too overwhelming. In fact, the cognitive system is effective in overcoming some of the coordination difficulties using an intervention that emphasizes "top-down" therapy methods (Smits-Engelsman et al., 2013). The top-down method requires distinct task goals that can be defined by components that are verbally mediated; the child is encouraged to stop and evaluate errors and verbalize a different strategy for the next trial. Thus, rather than depending on the motor system to perform some automatic tasks such as balance reactions, the child's attention is routed to very explicit cognitive strategies. Children with DCD often have a comorbidity of attention deficit disorder (Cruddace & Riddell, 2006). Children with both DCD and attention deficit disorder have a higher incidence of mental health problems and depression as they become adolescents and upon reaching adulthood (Missiuna et al., 2014). One speculation is that the difficulty of allocating attention in the case of struggling with both disorders concurrently strains the social and emotional capacity of the growing child.

Children with difficulties in either cognitive or attentional systems have been shown to have problems in dynamically controlling resource allocation during functional tasks. Children with intellectual disabilities show strong correlations between cognitive and motor scores (between 0.61 and 0.94) compared to weak correlations between motor and cognitive scores in children with typical development (between 0.24 and 0.56) (Houwen, Visser, van der Putten, & Vlaskamp, 2016). For children with intellectual disabilities the correlation between cognitive skills and both fine (0.94) and gross motor scores (0.76) is strong. The strong association between motor and cognitive skill in children with intellectual delays highlights the importance of shared resources between these areas, as well as justifying the necessity for early intervention to advance both areas.

7.3 Implications for Intervention

In both the medical model and the educational model, intervention for infants and children with developmental delays is compartmentalized such that the motor and cognitive areas are addressed separately. Although early interventionists value early motor skills as goals, the focus is often solely on motor milestone achievement (Palisano, 1991) without association to the cognitive implications of the movement (Mahoney, Robinson, & Perales, 2004). The implications of the concept of cognition–action trade-offs blend these two traditionally divided areas of development and suggest that there are strong reasons for intervention to serve and support cognitive and motor systems simultaneously. We propose several principles for early intervention stemming from the cognition–action trade-off concept:

1. Infants with early motor dysfunction may face challenges in cognitive development as well; the motor and cognitive systems cannot be readily separated as basic motor skills are developing. As infants gain postural control in sitting and standing, they begin to understand new spatial concepts (Soska, Adolph, & Johnson, 2010). Reaching and manipulation bring new challenges and eventual problem solving (Achard & von Hofsten, 2002), and mobility skills support the emergence of object permanence (Campos et al., 2000). As interventionists evaluate and determine deficits and goals for individual children, they must recognize that one system cannot be advanced in isolation without effects on the whole child. Pushing the motor system ahead without an understanding of the resources needed for cognitive gains may do harm to the overall advancement of the child.
2. Early examination of attention (including looking behavior) and the ability to switch attention, focus and redirect focus, should be part of early infant assessment as well as ongoing monitoring. Because both visual attention and focused attention are predictive of future cognitive skill, and they have been shown to be malleable and responsive to motor change, interventionists can utilize looking behaviors and attention as a window into the cognitive system. The effect of changes in the motor system on cognition can be documented through the lens of visual attention. In the current age of digital video via smartphone or digital tablet, the changes in attention of an infant in real time are easily monitored and can be archived for future reference and comparison.
3. Infants' cognition–action trade-off capability can be utilized as a mechanism to channel effort toward specific areas; in other words, a "cognitive" task can be made easier simply by altering the motor demands of said task (see Video 1 in the online version at https://doi.org/10.1016/bs.acdb.2017.11.001). Posture can be supported externally and intermittently to allow for allocation of attention to a new cognitive task. Conversely, when a posture has developed to a stable end, cognitive challenges can be ramped up.

Video 1 New sitter, unable to find a hidden toy in sitting, lays down to find object.

4. Interventionists can easily build upon a cognitive construct by incrementally creating challenges to the motor system. For example, in a means-end task, the interventionist could start the task with the child sitting with a towel pull to retrieve a toy, then advance to a string pull (harder to grasp), then to a stretchy string pull to create different motor parameters, or add resistance to change the strategy needed for success—one could add a ramp, or add a barrier to the task of retrieving the toy as well. All of these options increase the motor demand and will build movement skill while guiding the cognitive system to greater problem-solving capacity. Of course, the allocation of attention must be monitored to guide the child in such a way that the challenge is "just right" and incremental for eventual success.

8. CONCLUSIONS

In a longitudinal version of the A-not-B manual search task, the ability to inhibit the prepotent response *decreased* from 5 months (not yet sitting, poor reaching) to 8 months (independent sitting, good reaching) (Clearfield, Diedrich, Smith, & Thelen, 2006). Given the recurring theme throughout this chapter that expertise frees up attentional resources to improve executive functioning, why would expert reachers perseverate, but not novices? This counterintuitive example illustrates the importance of considering what happens to behavior as experience accrues. In this case, reaching expertise created a scenario in which the kinematics of infants' reaches were highly similar on every A trial of the task. In contrast, the novice reachers were highly variable across reaches as they were in the midst of gaining control over their arm movement. As a result, the assumption on which the A-not-B task hinges—that the switch trial would be difficult because infants would have to stop a behavior that they executed repeatedly—turns out not to be true in this case because the novice reachers had not, in fact, been instantiating the reaching behavior. This "exception to the rule" highlights the ongoing periods of physical change marked by rolling windows of instability that make infancy unique. We started this chapter by summarizing the work on attention in older children and adults; however, older children and adults bring stability of skill with them to dual tasks and other indices of attention. Future work must consider the extent to which this is generalizable to an infant population and whether the difference in stability renders the two groups incommensurate.

One of the key questions posed by attentional resource theories is whether there is "a central, unitary pool …or…multiple pools of resources" (Park, Kim, & Chun, 2007, p. 1063). The myriad examples of trade-offs between cognition and action summarized in this chapter suggest competition within a single pool of attentional resources for those domains. Time and again, when attentional resources are taxed in infancy, regardless of posture, we see the selection of balance control at the expense of the cognitive demands of the task. A key characteristic of internal attention is that it supports vigilance (Chun et al., 2011). This is relevant for infants who are still exploring and discovering new strategies. Part of the discovery seems to be improving a new skill or strategy so that it can be maintained for a useful duration.

Developmental care for infants and children with developmental delays or dysfunction could benefit from consideration of the concept of resource allocation and trade-offs between cognition and action. Most investigations of intervention efficacy for infants with a movement disorder, such as CP, do not consider the effect of poor movement control on cognition, nor is intervention planned with the interaction of motor and cognitive systems in mind (Lobo et al., 2013). The understanding of the importance of attention, and the relationship of shared attention between systems as new skills are learned, may be central to scaffolding additional functional abilities during developmental intervention. Future directions for investigation include: (1) detailed descriptions of the effect of motor skill acquisition in infancy and the trajectory of change in cognitive skill as specific motor skill expertise is reached; (2) determination of the cognitive constructs that are most closely associated with motor skill change over time; (3) longitudinal studies to exam the dynamic fluctuation that may occur in both cognitive and motor skills, and the relationship to attentional resources; and finally, (4) translation of research findings to varying groups of children in different diagnostic categories, so that findings can assist in developing innovative intervention techniques suitable to children with a variety of motor or intellectual disorders.

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