The development of cognitive control from infancy through childhood

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The Development of Cognitive Control From Infancy Through Childhood

Katherine C. Morasch, Vinaya Raj, *and* Martha Ann Bell

Abstract

Cognitive control is a strategic, regulatory ability guiding and organizing thoughts and actions that lead to goal-directed behavior. As such, it is a critical aspect of cognitive development and fundamental to higher order processing. In this review, we focus on the developmental periods of infancy through childhood to examine the early foundations of cognitive control. We adopt a dual-process theory of executive function, highlighting working memory and inhibitory control, as we discuss individual differences in behavioral and physiological mechanisms contributing to the development of cognitive control. We conclude with a discussion of the educational implications related to differences in this ability as well as suggestions for future research.

Key Words: cognitive control, early development, working memory, inhibitory control, frontal lobe

One of the most critical issues in contemporary cognitive development focuses on early executive functions and the neurological systems that support the foundations of these abilities. In this chapter, we approach executive functions from the perspective of cognitive control, an organizing process guiding goal-related actions. We first describe the defining characteristics of cognitive control, including an emphasis on working memory and inhibitory control mechanisms. Next, we detail typical tasks used in the study of early behavioral development of cognitive control. Then, we selectively review empirical studies examining the developmental psychophysiology of cognitive control in infancy and childhood. Finally, we discuss the implications of individual differences in cognitive control as well as potential research questions on higher order cognitive abilities in early development.

Characteristics of Cognitive Control

Executive functions refer to a collection of higher order cognitive processes responsible for organizing and coordinating behavior in order to perform complex goal-related actions (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). These include planning, set shifting, error detection and correction, working memory, and inhibitory control (Blair, Zelazo, & Greenberg, 2005; Roberts, Robbins, & Weiskrantz, 1998). One of the main questions in the study of higher order processes is whether executive function operates as a unitary construct or whether its subcomponents should be examined in isolation (Eslinger, 1996; Garon, Bryson, & Smith, 2008; Miyake et al., 2000; Roberts & Pennington, 1996). Our conceptualization of executive function aligns with Roberts and Pennington's interactive framework.

In describing their framework of executive function, based on prefrontal cognitive processes, Roberts and Pennington (1996) suggest that the umbrella term of "executive functions" could effectively be reduced to a smaller set of core processes. They propose that the two main executive functions that best represent the role of the prefrontal cortex are working memory (the ability to sustain and manipulate short-term information needed for

performing future action; Baddeley, 1986; Reznick, 2007) and inhibitory control (the ability to inhibit inappropriate or inaccurate action, such as a prepotent response; Diamond, 1990; Goldman-Rakic, 1987).

Working memory (WM) is assumed to involve maintaining transient information in short-term storage while actively manipulating or "working" with that information in order to achieve a goal (Baddeley, 1986; Pennington, 1994). This goal may be externally defined, or it may be as basic as the intrinsic desire to not make an error. WM is thought to have a limited capacity that is constrained by the amount of information that can be held and manipulated simultaneously and by the length of time that information can be kept online (Baddeley, 1992; Kane & Engle, 2002).

Baddeley (1986) provides a well-established, comprehensive theory of WM. In his updated model, Baddeley describes WM as being parsed into three slave systems, a visuospatial sketchpad, a phonological loop, and an episodic buffer, which are organized by a central executive regulatory component (Baddeley, 2000). The central executive is viewed as having a coordinative function (Baddeley, 1992), directing attention, and balancing the storage and active requirements inherent in WM processing.

Inhibitory control (IC) is a central component of executive function and generally focuses on the ability to actively inhibit or delay a dominant response to achieve a goal (Roberts & Pennington, 1996). As in real-world situations demanding inhibitory abilities, what is being inhibited varies as a function of experimental task. Thus, inhibited responses may include reflexive reactions in response to external stimuli (e.g., antisaccade tasks), as well as learned automatic responses to more cognitively demanding tasks (i.e., go/no-go and Stroop tasks). In these tasks, individuals may be required to suppress reactions to recently established rules or perhaps to focus on local characteristics (color of printed words) in the face of more salient, automatic responses (reading a printed word). Although these tasks elicit inhibitory abilities in different ways, they all require top-down control of behavior (Kok, 1999).

In summary, WM processes are required for producing and performing correct responses, whereas IC is necessary for suppressing interfering dominant responses (Roberts & Pennington, 1996). Whereas WM and IC can each be considered independently to characterize specific aspects of cognitive regulation (Demetriou, Christou, Spanoudis, & Platsidou,

2002; Luna, Garver, Urban, Lazar, & Sweeney, 2004), there is evidence that WM and IC work in concert to support goal-driven behavior (Miller & Cohen, 2001; Roberts & Pennington, 1996; Wolfe & Bell, 2004, 2007). Roberts and Pennington (1996) argue that an interactive, dual-component process, comprised of WM and IC, functions distinctly from either process in isolation. We consider this interactive skill, WMIC, to underlie the executive process known as cognitive control.

The term *cognitive control* was first described by Posner and Snyder (1975) in a chapter contrasting automatic activation processes against more strategic or conscious controls of behavior and/or cognition. More recently, cognitive control has been defined as the strategic, regulatory ability guiding and organizing thoughts and actions that lead to goal-directed behavior (Davidson, Amaso, Anderson, & Diamond, 2006; Luna, Padmanabhan, & O'Hearn, 2010). We conceptualize cognitive control as frontally mediated executive abilities binding WM and IC into the interactive component WMIC (Davidson et al., 2006; Luna et al., 2010; Roberts & Pennington, 1996).

In our program of research, we examine cognitive control based on the model of executive processes set forth by Engle and colleagues (Barrett, Tugade, & Engle, 2004; Engle, Kane, & Tuholski, 1999; Unsworth, Schrock, & Engle, 2004). Engle characterizes WM as a system of highly salient long-term memory traces that are held active above a threshold via short-term memory representational abilities. Included in this description are the skills and processes necessary to achieve and maintain this activation, as well as a limited-capacity, domain-general attentional control component responsible for the regulation of higher level cognitive demands. The function of this executive attention component is perhaps the most intriguing part of Engle's model and effectively captures our conceptualization of cognitive control (Bell & Morasch, 2007).

Similar to Engle and colleagues' description of a controlled attentional capacity, cognitive control is the maintenance of short-term memory representations in the presence of interference or response competition. In the absence of interference, various components of information, goals, and planned actions are accessed from long-term memory stores with few errors. However, when faced with interfering conditions, it is likely that inaccurate information and incorrect responses are produced (Kane & Engle, 2002). Thus, cognitive control is not needed for all mental processing, but it is elicited

in circumstances that require response inhibition under cognitively challenging conditions (Engle et al., 1999; Unsworth et al., 2004).

Additionally, this domain-general executive attention ability of cognitive control has been shown to predict performance on higher order cognitive tasks (Kane & Engle, 2002). Individual differences in executive attention (Engle et al., 1999; Kane & Engle, 2002, 2003; Unsworth et al., 2004) have been associated with a wide variety of cognitive abilities, including general fluid intelligence (Engle et al., 1999). According to Engle's model, these individual differences in cognitive control reflect the ability to apply activation to short-term memory representations, to bring these representations into focus and actively maintain them, and to do so in the face of interference or distraction (Engle et al., 1999; Kane & Engle, 2003). Therefore, individuals who score high on tasks assessing cognitive control are more effective at ignoring task-irrelevant information and maintaining a focus on pertinent information than individuals low in cognitive control. Indeed, individuals who are low in cognitive control have been described as more likely to break focus and orient to distracting, attention-capturing external cues (Unsworth et al., 2004). In addition to emphasizing the central role of the attentional control component, Engle and colleagues assert that this model can be appropriately applied to research with children and that individual differences in this ability are likely supported by prefrontal mechanisms (Engle et al., 1999).

Early Behavioral Development of Cognitive Control

Individual differences in executive function have been associated with developmental improvements in socialization (Hughes, Dunn, & White, 1998), conscience (Kochanska, Murray, & Coy, 1997), and school readiness (Blair, 2002; Diamond, Barnett, Thomas, & Munroe, 2007). Age-related changes in cognitive control, operationally defined as WMIC performance, have been examined behaviorally (Davidson et al., 2006; Diamond, Prevor, Callender, & Druin, 1997; Gerstadt, Hong, & Diamond, 1994; Welsh, Pennington, & Groisser, 1991), electrophysiologically (Bell, 2001, 2002; Bell & Fox, 1992, 1997), and neuroanatomically (Casey et al., 1997; Diamond, 1990, 1991; Diamond & Goldman-Rakic, 1989; Diamond, Zola-Morgan, & Squire, 1989). The converging evidence from these studies suggests that the biological substrates of successful performance on WMIC tasks are developing

throughout infancy, toddlerhood, and the early childhood period.

Investigations of WMIC abilities often highlight cognitive tasks that require the participant to hold some information in memory and to simultaneously inhibit a prepotent response. Significant changes in WMIC processes are clearly identifiable from infancy through early childhood. As is the case with executive functions in general, there is currently no universal agreement on a single unifying measure of WMIC, and there are multiple approaches to the study of this ability (Blair, Granger, & Razza, 2005; Carlson, 2005; Diamond et al., 1997; Espy, 2004). We will discuss relevant tasks and age-related trends in cognitive control measured across early development. As we discuss these studies, it will be evident that most are correlational in nature, although the assumption is that brain maturation is driving these trends in developmental processes (Diamond, 2002).

In infancy, one age-appropriate WMIC task is Piaget's (1954) classic A-not-B task, which is comparable to Jacobsen's (1935) delayed response paradigm (Bell & Fox, 1992, 1997; Bell & Morasch, 2007; Diamond, 1990; Diamond et al., 1997; Pelphrey et al., 2004; Reznick, 2007). Although one recent framework of executive functions in childhood describes the A-not-B task as a measure of set shifting (Garon et al., 2008), the work of Diamond and others focuses on the executive functions of WM and IC as critical for success on this task (Braver & Barch, 2002; Diamond et al., 1997, Roberts & Pennington, 1996).

In the A-not-B task, a toy is hidden in one of two locations (i.e., A or B) in full view of the infant and then the infant is encouraged to "find the toy." After two correct searches to location A, the infant observes as the toy is hidden in the opposite location, and the infant is again encouraged to find the toy. Infants younger than 8 months have the tendency to search for the toy at location A, not location B, even though they observed the toy being hidden at B. Research and theory about this phenomenon maintain that successful performance on this task (i.e., searching at location B) requires simultaneous cognitive skills of WM and IC. Indeed, infants are required to constantly update and maintain knowledge of where the toy is hidden as subsequent trials occur, and to simultaneously inhibit the prepotent response to search at the location where they were previously rewarded. With age, infants become more successful in correctly searching at location B, even after a brief delay (Diamond, 1990; Diamond et al., 1997).

During the toddler period, individual differences in language ability are markedly high. Therefore, similar to the testing demands in place during infancy, toddler WMIC has often been examined using nonverbal assessments of visuospatial conflict (Diamond et al., 1997). Similar to the classic infant A-not-B task, success on the A-not-B task with invisible displacement requires the toddler to be able to remember where a reward is hidden across a 5-second standard delay and to inhibit responding based on the location of previous rewards (i.e., conflicting conditions; Diamond et al., 1997). In this task, a toy is hidden at a central location and the hiding apparatus is shifted to a lateral location in full view of the child. A barrier is placed between the child and the hiding location, and during a brief delay period, a second potential hiding location is added behind the barrier. Following the delay, the barrier is lifted and the child is allowed to search. Just as with the infant A-not-B task, the child accrues two consecutive correct responses on the same side and then the hiding location is switched to the opposite side. As consecutive correct responses accrue to same-side trials, so does the prepotency of the dominant response to return to the location of previous reward. Thus, the reversal trials, ones where the hiding location is switched to the opposite side, are the source of WMIC-related conflict-based behavior. As during infancy, with age, toddlers' accuracy increases on reversal trials (Diamond et al., 1997).

WMIC tasks that have been used with children from 3½ to 7 years of age include Stroop-like tasks such as Day/Night (Carlson, 2005; Diamond et al., 1997). In the Day/Night task, children are instructed to say "day" when they are shown a drawing of a yellow crescent moon and stars on a black card and are instructed to say "night" when shown a yellow sun on a white card. Children, therefore, are required to remember two rules (i.e., the instructed responses for each picture stimulus) and to also inhibit a dominant response (i.e., the tendency to label the picture with the congruent label). Because successful performance on the Day/Night task involves WMIC skills, it is hypothesized to involve prefrontal functioning as well. The percentage of correct response on this Stroop-like task increases with age (Carlson, 2005; Diamond et al., 1997; Wolfe & Bell, 2007).

In a recent examination of the development of cognitive control from 4–13 years of age, Davidson et al. (2006) found that WM tasks which included IC demands accounted for more variability in performance in younger children than in older children and adults. Indeed, using spatial tasks presenting either congruent or incongruent stimuli and response expectations, Davidson et al. (2006) showed that the incongruent trials were more difficult overall, and these interfering effects were most pronounced for younger children. Additionally, even the 13-year-olds were affected by the more challenging conditions of tasks assessing both WM and IC, rather than just one or the other.

One interesting finding from Davidson and colleagues' (2006) work was that as age-related IC abilities improved, WM capacity demands became more challenging relative to inhibitory demands. Indeed, due to immaturity of inhibitory skills, younger children's performance was more susceptible to interference from distracters, which acted to mask WM success in tasks presenting conflicting conditions (Bjorklund & Harnishfeger, 1990; Luna et al., 2010). Before age 10, introducing distracting or conflicting task demands resulted in more dramatic losses in performance accuracy than did taxing the capacity of working memory. The opposite trend was true for older children. Additionally, across age, performance on tasks specifically designed to separately assess either WM or IC control were highly correlated with one another (ranging from 0.7 to 0.8; Davidson et al., 2006). Thus, it may be that the interactive components of WMIC are codeveloping throughout this childhood period.

Neural Correlates of Cognitive Control Development

In our examination of the role of prefrontal function, we highlight our own research on the development of individual differences in cognitive control, as well as selectively review the work of others. Our research takes a decidedly psychobiological approach to examine cognitive control performance, focusing on behavior as well as patterns of brain electrical activity associated with WMIC task performance. The focus of our research program is one of individual differences in frontal lobe development, with an emphasis on WMIC components of cognitive control.

Evidence from atypical and healthy populations has consistently highlighted the integrity and function of the frontal lobe as the neurological substrate for the development and function of executive processes (Diamond, 2001; Diamond et al., 1997; Nelson & Luciana, 2008; Welsh & Pennington, 1988). Additionally, within both the human and nonhuman primate literatures, it has

been hypothesized that individual differences in cognitive control are associated with individual differences in the functioning of the prefrontal cortex (Astle & Scerif, 2008; Davidson et al., 2006; Goghari & MacDonald, 2009; Kane & Engle, 2002; Luna et al., 2010). Indeed, Miller and Cohen (2001) strongly argue that the capacity for cognitive control is the primary function of the prefrontal cortex. Anatomical, neuropsychological, and biobehavioral work with developmental populations have all implicated the unique development and function of the frontal cortex in supporting individual and age-related differences in WMIC mechanisms (Bell & Morasch, 2007; Bell & Wolfe, 2007a; Diamond, 2001, 2002; Diamond et al., 1997; Luria, 1973; Morasch & Bell, 2011; Passler, Isaac, & Hynde, 1985). For example, behavioral neuroscience investigations reveal that tasks tapping the integration of WM and IC are dependent on the prefrontal cortex and lesions to this area, specifically the dorsolateral prefrontal cortex, impair WMIC performance (Diamond, 1988, 1990; Diamond & Goldman-Rakic, 1989). Despite direct calls for work focusing on neural correlates of executive function development, including WMIC and other processes (Diamond, 2002; Diamond et al., 1997; Reznick, 2007), there remain few empirical investigations directly exploring the biobehavioral expression of WMIC in early development.

The development of the neural circuitry that subserves cognitive control, particularly the prefrontal cortex, is delayed compared to other cortical regions (Goldman-Rakic, 1987; Goldman-Rakic & Leung, 2002). The presence of this delayed maturation is evident in resting metabolism (Chugani, 1994, 1998; Chugani & Phelps, 1986), cortical gray matter reduction (Giedd et al., 1999), increases in cerebral white matter (Jernigan et al., 1991), and changes in synaptogenesis (Huttenlocher, 1979; for reviews, see Casey, Geidd, & Thomas, 2000; Diamond, 2002). Indeed, the frontal lobes are typically not functionally mature until the second half of the first year of life, as indicated by associations with WMIC task performance (Bell & Fox, 1994). Additionally, the development of frontal architecture is also protracted, as it continues to structurally develop from infancy through early adulthood (Luna et al., 2004). Evidence that age-related improvements in WMIC skills develop gradually throughout childhood lends support to the hypothesis that the immaturity of the prefrontal cortex is a limiting factor in the development of cognitive control.

A useful strategy in exploring the neural processes associated with these early executive function skills is to employ psychophysiological recording techniques that allow for the examination of age-related changes in brain functioning during cognitive processing. More specifically, the electroencephalogram (EEG) is advantageous as an electrophysiological technique because it provides a method for relating brain development to resting and activity-related differences in cognitive processing. The EEG records brain electrical activity emitted from the scalp, with the assumption that these electrical signals originate from the brain itself (Berger, 1929, 1932; Stern, Ray, & Quigley, 2001). EEG is advantageous in developmental research settings because it is relatively inexpensive, noninvasive, easily used with infants and children, and offers greater temporal resolution of brain–behavior processes (Bell & Wolfe, 2007b; Bell, Wolfe, & Adkins, 2007; Casey & de Haan, 2002) than more metabolic-based measurements. Taking these advantages into account, our research program has relied heavily on incorporating EEG technology to the study of early cognitive functions and changes in brain development. While relatively few developmental investigations have explored the direct link between changes in prefrontal functioning and improvements in cognitive control, we attempt to offer a selective review of the psychophysiological literature exploring these associations from infancy, toddlerhood, and early childhood.

As previously noted, successful performance on the infant A-not-B task has been anatomically linked to the integrity and development of the dorsolateral prefrontal cortex (Diamond & Goldman-Rakic, 1989; Diamond, Zola-Morgan, & Squire, 1989; Nelson, 1995). EEG studies measuring changes in brain electrical activity have provided a great deal of insight to understanding the relations between frontal lobe development and WMIC processes associated with the A-not-B task. In a longitudinal assessment, Bell and Fox (1992) reported that baseline frontal EEG power from 7 to 12 months was associated with performance on a reaching A-not-B task. EEG power reflects the excitability of groups of neurons, and increases in power values during infancy are considered to be a marker of brain maturation (see Bell, 1998; Bell & Fox, 1994 for reviews). In this study, infants who by 12 months of age were able to tolerate long delays between hiding of the object and subsequent manual search on the A-not-B task exhibited greater increases in baseline frontal and occipital EEG power across age

from 7 to 12 months, whereas infants who were unable to tolerate such delays by 12 months did not display these changes in power values. The association between EEG power values and A-not-B task performance was replicated in an age-held-constant study with a sample of 8-month-olds. Specifically, higher levels of task performance were associated with greater baseline EEG power values at frontal and occipital scalp locations (Bell & Fox, 1997).

In subsequent research investigations utilizing task-related EEG, we demonstrated that infants with higher levels of performance on a looking version of the A-not-B task exhibited baseline-to-task increases in EEG power values at frontal and posterior scalp locations. This was observed specifically during the delay phase of the toy-hiding procedure when WMIC demands are highest. However, infants with low levels of performance had task-related EEG power values that did not differ from their baseline values (Bell, 2001). Importantly, task-related EEG was able to not only distinguish between high and low levels of overall performance but also between correct and incorrect individual responses during the looking A-not-B task (Bell, 2002). Taken together, these data demonstrate links between emerging WMIC skills and frontal and some posterior involvement during infancy.

Much less is known about the psychophysiological changes associated with executive functioning skills during the toddler period. As noted by Diamond (2002), relatively little is known about frontal lobe maturation between the ages of 1 and 3 years, and the developmental psychophysiological literature is limited with respect to EEG data during the toddler period (Bell & Wolfe, 2007b). To our knowledge, Morasch and Bell (2011) provide the first known investigation describing patterns of brain electrical activity during WMIC function in toddlers. This study gave special focus to the cognitive control component of inhibitory functioning, which can be regarded as a particularly salient skill necessary for both higher order cognitive processing and self-regulation during the toddler years. Baseline-to-task changes in EEG power were examined during a looking version of the A-not-B task with invisible displacement, which taps the executive skill of WMIC (Diamond et al., 1997) and allows for the recording of continuous EEG during task performance. Results demonstrated that changes in brain electrical activity at medial frontal, parietal, and occipital scalp locations uniquely predicted maternal ratings of toddler inhibitory control, even after controlling for concurrent WMIC

task performance on A-not-B task (Morasch & Bell, 2011). These findings coincide with previous investigations implicating the role of frontal lobe activity in cognitive control function, and they are particularly exciting because they provide the first known simultaneous exploration of WMIC and continuous EEG during the toddler period.

Relatively few research investigations have explored EEG studies of cognitive control in early childhood. In our research lab, we have extended our infant and toddler investigations of the beginnings of WMIC skills and their associated patterns of electrophysiology to the preschool years. Wolfe and Bell (2004) investigated the neural correlates of WMIC in a sample of preschool children, aged 4.5 years. Patterns of baseline-to-task changes in EEG power values were compared using age-appropriate WMIC tasks, such as the Day-Night Stroop (Diamond et al., 1997). Results from this study provided further confirming evidence linking physiological changes in cognitive control to frontal lobe involvement in early childhood. Specifically, baseline-to-task increases in EEG power at the medial frontal region (assumed to reflect prefrontal cortex activation) were evident in children who demonstrated higher levels of WMIC performance, in contrast to the low-performance group, which showed no task-related changes in EEG power (Wolfe & Bell, 2004). This pattern of frontally mediated differences related to WMIC performance echoes our findings in infancy and toddlerhood.

In a longitudinal study, Bell and Wolfe (2007a) examined both the developmental progression of executive function skills from infancy to early childhood and the corresponding changes in brain maturation that take place during this time span. A comparison of patterns of brain electrical activity during WMIC processing between infancy and early childhood revealed a pattern of widespread brain electrical activity during infancy, as reported earlier. More specifically, increases in EEG power from baseline to task were evident at frontal scalp locations as well as across the entire scalp (Bell & Wolfe, 2007a). In contrast, when these same infants reached 4.5 years of age, a more specified pattern of frontal activation emerged, signifying that WMIC processing may have become more localized to frontal brain areas.

Exploring age-related changes in WMIC functioning during early childhood, Wolfe and Bell (2007) examined three groups of children (3½-, 4-, and 4½-year-olds) to further pinpoint when during this developmental period brain functioning

becomes more specified. Wolfe and Bell (2007) showed that with increasing age-related specificity, WMIC processing depended on frontal lobe activation. Additionally, increases in EEG power at left medial frontal scalp locations were able to explain variability in WMIC performance above and beyond the variable of age (Wolfe & Bell, 2007).

Although baseline to task increases in EEG power values have been associated with the development of WMIC in infants, toddlers, and children, functional magnetic resonance imaging (fMRI) data have been collected with 7- and 8-year-olds using a go/no-go IC reaction-time task that induced conflict between responding and withholding a response (Casey et al., 1997; Durston et al., 2002). This work has shown cortical activation along the frontal midline, rather than from diffuse cortical sites. This is a notably different pattern of activation than was found in the infant, toddler, and preschool EEG research, where most scalp locations were indicated, and may reflect increasing specificity with development. EEG replication of this fMRI WMIC activation pattern in young children is needed and would validate EEG as a psychophysiological measure of cognitive control in young children.

Implications and Future Directions

The development of cognitive control has implications for adjustment in many areas of functioning. Cognitive control is a critical component for higher order cognitive functioning, and the early development of cognitive control processes has implications for school readiness and later academic success (Blair et al., 2005; Diamond et al., 2007; Gathercole & Alloway, 2006). Recent conceptual and empirical work suggests that regulatory control over behavior, including cognitive and emotion control, is a better predictor of successfully transitioning into the school setting than actual scholastic knowledge (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Blair, 2002; Denham, 2006).

From a purely cognitive point of view, however, knowledge about early developing WMIC skills is critical for understanding early academic performance. For example, WM predicts emerging mathematic skills in preschool children (Espy et al., 2004) and poor WM performance at age 5 is associated with poor reading assessments at age 8 (Gathercole, Tiffany, Briscoe, & Thorn, 2005). Thus, there is an important need for accurate diagnosis and remediation of poor WM skills.

Gathercole and colleagues have proposed a method for diagnosing WM impairments and have recently reported on a training technique to enhance poor WM in older children (Gathercole & Alloway, 2006; Holmes, Gathercole, & Dunning, 2009). WM is considered to be impaired if a child falls one standard deviation below the mean on typical forward and backward digit span tasks or on a standardized battery, such as the Working Memory Test Battery for Children (Gathercole & Alloway, 2006; Pickering & Gathercole, 2001). The training task used with a group of 10-year-olds by Gathercole and colleagues consisted of a variety of computerized WM games with which the children engaged for 35 minutes a day for at least 20 days across a 6-week period of time. The tasks were adapted to each child's current WM skills so that participating in the computerized games taxed the limits of WM for the individual child. Participation in this behavioral intervention increased the WM skills of the children to age-appropriate levels and the increase in WM was sustained with respect to a 6-month follow-up assessment (Holmes et al, 2009). These enhancements in WM were relative to children who participated in computerized WM games that did not tax WM skills. Furthermore, the children's mathematical skills also improved following the taxing WM training, demonstrating that scholastic achievement was enhanced with the training of WM skills in middle childhood.

Arguing that executive function skills, particularly those associated with WM and IC, need to be improved prior to school entry, Diamond and colleagues assessed the Tools of the Mind curriculum for efficacy in improving cognitive control in low-income children attending preschool (Diamond et al., 2007). The Tools curriculum consists of a series of games and activities designed to promote cognitive control skills throughout the preschool day. Relative to children in a preschool curriculum that did not focus on cognitive control games, children in the Tools curriculum performed higher on WMIC tasks. It is important to note that the tasks used at assessment were different from the tasks/games on which the children were trained. Furthermore, performance on the cognitive control outcome tasks was correlated with reading readiness scores (Diamond et al., 2007).

Our goal in this chapter has been to demonstrate that the development of cognitive control is multifaceted in infancy and childhood. We have focused on behavioral and cortical indicators of WMIC development, as well as academic correlates of early WMIC skills. We briefly highlighted two training programs, one designed to enhance WM skills in

school-aged children who are deficient in this cognitive control skill and another designed to enhance WMIC skills in preschool children who are at risk for academic difficulties. Although we did not focus our review on situational influences on the development of cognitive control, we conclude by briefly noting the potential for environmental factors to impact early WMIC development.

In the developmental psychology literature, much attention has been given to the role of maternal interactive style on child emotion control (e.g., Calkins & Bell, 2010); however, little attention has been given to the potential role of parenting behaviors in the development of executive functions. Colombo and Saxon (2002) argue that perhaps individual differences in early memory and attention abilities interact with characteristics of parental caregiving behaviors to influence child cognitive development. Studies designed to determine how parents influence child cognitive control would fill a major void in the cognitive development literature.

Finally, the functional architecture of the prefrontal cortex continues to develop through adolescence and into early adulthood (Luna et al., 2004) and exhibits age-related changes toward the end of the life span. Evidence from the adult cognitive neuroscience and cognitive aging literatures indicates that performance on executive function tasks is dependent on the integrity of the prefrontal cortex across adulthood (Miller & Cohen, 2001; Luna et al., 2010). Further cross-sectional and longitudinal studies examining factors contributing to the expression of higher order abilities in early, middle, and late adulthood will contribute to the complete picture of the development of cognitive control.

Acknowledgments

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