

A Developmental Perspective on Executive Function

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This review article examines theoretical and methodological issues in the construction of a developmental perspective on executive function (EF) in childhood and adolescence. Unlike most reviews of EF, which focus on preschoolers, this review focuses on studies that include large age ranges. It outlines the development of the foundational components of EF—inhibition, working memory, and shifting. Cognitive and neurophysiological assessments show that although EF emerges during the first few years of life, it continues to strengthen significantly throughout childhood and adolescence. The components vary somewhat in their developmental trajectories. The article relates the findings to long-standing issues of development (e.g., developmental sequences, trajectories, and processes) and suggests research needed for constructing a developmental framework encompassing early childhood through adolescence.

Broadly defined, executive functions (EFs) encompass those cognitive processes that underlie goal-directed behavior and are orchestrated by activity within the prefrontal cortex (PFC; e.g., Olson & Luciana, 2008; Shimamura, 2000). Children's EF has been of great interest to developmental psychologists in recent years. However, this research has three limitations that pose difficulties for constructing a truly developmental account of EF. First, most research on the development of EF has examined narrow age ranges, for example, 2–5 (Isquith, Gioia, & Espy, 2004). Second and relatedly, most research has focused on preschoolers (e.g., Carlson, 2005; Garon, Bryson, & Smith, 2008), perhaps because rapid improvements occur during the preschool and early school years on EF tasks (e.g., Carlson & Moses, 2001; Zelazo, Muller, Frye, & Marcovitch, 2003). However, performance on other, more complex tasks does not mature until adolescence or even early adulthood (e.g., Anderson, 2002; Conklin, Luciana, Hooper, & Yarger, 2007; Davidson, Amso, Anderson, & Diamond, 2006; Luciana, Conklin, Hooper, & Yarger, 2005; Romine & Reynolds, 2005). Moreover, the rudiments of EF emerge before early childhood, likely within the 1st year of life (e.g., Diamond, 1990a, 1990b). Third, we have

little information about the processes by which children move from one level to another, especially processes operating after age 5.

Consequently, despite the large literature on EF in children, we have no truly developmental account of EF across childhood and adolescence. The purpose of this article is to begin to construct such an account, which distinguishes it from previously published reviews of EF (but see Best, Miller, & Jones, 2009). We focus on the few studies that include a large age range in an attempt to outline the broad developmental trajectories of EF and look at the development of EF within the framework of developmental theoretical issues.

After a brief presentation of theoretical and methodological challenges to a developmental account of EF, the main part of the review examines changes in three components of EF across multiple ages. Then we address developmental trajectories, sequences of the components, and mechanisms of development, and suggest future research to examine basic issues of development.

Theoretical and Methodological Challenges

Beyond the limitations of narrow age ranges and few studies examining developmental sequences and mechanisms, it is very difficult for other reasons to extract a general trajectory of EF development

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from the literature. A main challenge is the lack of agreement concerning whether EF is a unitary construct or a set of independent components (e.g., Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Brocki & Bohlin, 2004; Isquith et al., 2004; Miyake et al., 2000). One prominent theoretical framework integrates these opposing perspectives by suggesting that the EF construct consists of interrelated, but distinct, components—described as the “unity and diversity of EF” by Miyake et al. (2000). In their seminal study with young adults, Miyake et al. used confirmatory factor analysis (CFA) to test this framework. The CFA extracted three correlated latent variables from several commonly used EF tasks. These latent variables represented three EF components—inhibition, working memory (WM), and shifting—that contributed differentially to performance on complex EF tasks (Miyake et al., 2000; although Miyake recently—2009—has questioned whether inhibition can be considered a distinct component). Thus, although bound by some common underlying processes, in young adults EFs are distinguishable and are employed differentially based on the task at hand.

Some research with children has investigated the EF construct and has found at least partial support for an integrative framework. Hughes (1998) sought to expand a previous finding that EF consists of dissociable components in older children (Welsh, Pennington, & Groisser, 1991). She extracted three distinct factors—attentional flexibility, inhibitory control, and WM—from preschoolers’ performance on several EF tasks, suggesting that EF components are differentiated even at a young age. Both Hughes and Welsh et al. (1991) emphasize the independence of these factors, leaving little discussion of whether these factors may be interrelated. Senn, Espy, and Kaufmann (2004), also with preschoolers, used path analysis, which forms each latent variable by drawing on only one task rather than multiple tasks (which makes it more susceptible to extraneous influences such as test order and task reliability that may affect relations among the measures). Although performance on the WM and inhibition tasks was correlated and predicted complex task performance, shifting performance was unrelated to the other measures. This provided evidence that the EF components are dissociable in early childhood but also that those components are interrelated to some degree.

CFA with older children seems to provide stronger support for Miyake’s “unity and diversity view.” First, Lehto, Juujärvi, Kooistra, and Pulkkinen (2003) found that Miyake’s three-factor

model provided the best fit of data from children aged 8 to 13. Second, Huizinga, Dolan, and Van der Molen (2006) employed CFA in a more developmental fashion by comparing the models of 7-, 11-, 15-, and 21-year-olds. They found partial support for the Miyake model as only the WM and shifting measures loaded onto latent variables, whereas the inhibition measures did not load onto a common latent variable (see also Miyake, 2009, for similar results with adults). Importantly, this model was consistent across the age groups, suggesting the stability of the EF construct across middle childhood, adolescence, and early adulthood. Together, these studies provide considerable evidence that Miyake’s integrative model of interrelated, yet dissociable, EF components may be a suitable theoretical framework from which to examine EF development. However, these studies also suggest that the degree of unity and independence of the three components may change developmentally. This more complete picture of development and more nuanced version of the Miyake et al. model would be missed by focusing on only adults or a narrow age range on children, during the preschool years.

When a sample does include older school-age children and adolescents, methodological challenges can arise. First, to avoid ceiling effects researchers often use complex EF tasks that likely tap into multiple EFs, a problem of task impurity (Miyake et al., 2000). For complex tasks like the Wisconsin Card Sorting Test (WCST), the Tower of London (TOL), or Tower of Hanoi (TOH), task completion likely requires the coordination of multiple processes (e.g., Asato, Sweeney, & Luna, 2006; Huizinga et al., 2006; Miyake et al., 2000). However, for simplicity, researchers often classify tasks by a single cognitive construct. For example, the WCST and its child-appropriate version (DCCS) have been described as inhibition tasks by some and shifting tasks by others (Garon et al., 2008); the TOL and TOH have been described as either inhibition, WM, or planning tasks in various publications (e.g., Berg & Byrd, 2002; Huizinga et al., 2006; Welsh, Satterlee-Cartmell, & Stine, 1999).

Second, and very much relatedly, the tasks used across an age range often are not uniform. Tasks too difficult for the younger participants sometimes are only administered to the older ones, which makes comparisons across age groups difficult (e.g., Klenberg, Korkman, & Lahti-Nuuttila, 2001). Or very different tasks are used to assess a particular dimension for preschoolers and older children (e.g., Hughes, 1998; Welsh et al., 1991).

Keeping these issues in mind, we utilize Miyake's "unity and diversity" theoretical framework to focus on the "foundational" EFs—inhibition, information updating, and monitoring (WM), and shifting (Hughes, 1998; Huizinga et al., 2006; Lehto et al., 2003; Miyake et al., 2000)—in part because several frequently used cognitive tasks ostensibly tap into each dimension (Miyake et al., 2000). In using this framework to address EF development from early childhood through adolescence, we keep in mind current developmental theories of EF. In general, most of these theories depict EF development as involving an increasing ability to resolve conflict. They differ in whether this conflict is between rules that eventually become hierarchically organized (Zelazo et al., 2003), latent and active representations (e.g., habits vs. attention and WM; Munakata, 2001), or the current representation versus prepotent mental sets or behaviors (Diamond, 2006). Most also emphasize the role of changes in underlying neural networks. In particular, Posner and Rothbart (2007; see also Garon et al., 2008) propose that the development of the anterior attention system plays the major role in the resolution of conflict by regulating other brain networks. Posited developmental change is both qualitative (e.g., changing from simpler to more complex rule systems; Zelazo et al., 2003) and quantitative (e.g., strengthening active representations so that they override latent representations; Munakata, 2001).

We focus on those studies that most clearly address developmental issues—those that examine both preschoolers and school-age children, or school-age children and adolescents; address the order of acquisition of different aspects of EFs; or examine possible developmental processes. This approach permits us to detect developmental trajectories, sequences, and processes. Given a recent extensive review (Garon et al., 2008) of the large literature on the preschool age, only representative studies of this age are included.

Converging evidence and multiple levels of analysis are provided by studies using neuroscience techniques (e.g., functional magnetic resonance imaging [fMRI], event-related potential [ERP]) that assess the neural response underlying EF. It has been known for years that patients with PFC damage can have EF deficits yet normal IQ (e.g., Stuss & Benson, 1984). More recent thinking about this is that the PFC coordinates posterior cortical and subcortical brain activity via excitatory and inhibitory pathways (Casey, Amso, & Davidson, 2006; Shimamura, 2000). Moreover, PFC activity

holds relevant information in WM (e.g., "the cracker is hidden under the left cup") and prevents distracting information from entering WM (Goldman-Rakic, 1987; Olson & Luciana, 2008; Shimamura, 2000).

We also know from structural imaging studies (e.g., using MRI) that PFC development, like brain development more generally, consists of both progressive (e.g., myelination, neuron proliferation, synaptogenesis) and regressive (e.g., cell death, synaptic pruning; Casey et al., 2006; O'Hare & Sowell, 2008) changes. The PFC matures later in adolescence as evidenced by further loss of gray matter (Gogtay et al., 2004; O'Hare & Sowell, 2008), unlike many other brain regions that mature earlier (e.g., regions involved in attention, motor and sensory processing, and speech and language development). During this time, progressive and regressive changes (largely myelination and synaptic pruning, respectively) occur concomitantly and are driven in part by the child's experiences—the result being "efficient networks of neuronal connections" (O'Hare & Sowell, 2008, p. 24).

Developmental neuroscience studies can enrich our understanding of EF development by determining how the neural correlates of behavior change over time. Changes in neural correlates (i.e., the neural response underlying task execution), in turn, can be interpreted in light of the known structural development of the brain and of the PFC in particular. Alternatively, changes in brain structure can be correlated with changes in task performance to determine the relevance of structural changes to EF maturation. In either case, we must remember that both progressive and regressive structural changes may influence how the neural response changes over time.

Foundational Executive Functions

Inhibition

Inhibition is considered foundational for EF (e.g., Miyake et al., 2000); however, most inhibition tasks are not pure measures of inhibition (Simpson & Riggs, 2005) nor do they tap into a single inhibitory process (Nigg, 2000). Garon et al. (2008) distinguished simple from complex response inhibition tasks based on whether WM also is needed. Simple response inhibition requires a minimal amount of WM, making it one of the purest forms of inhibition (Cragg & Nation, 2008). It shows its rudiments during infancy (see Garon et al., 2008), as when a child can delay eating a treat. Complex response

inhibition also requires substantial WM by requiring that an arbitrary rule be held in mind or by requiring that the child inhibit one response (prepotent or not) and produce an alternative response. The day-night task assesses complex response inhibition by requiring the child to inhibit a prepotent verbal response (i.e., saying "day" upon viewing a picture of a sun) and activate an alternative verbal response (i.e., saying "night" upon viewing a sun; Gerstadt, Hong, & Diamond, 1994). Similarly, Carlson and Moses (2001), using factor analysis, distinguished delay tasks, which require withholding a propotent response, from conflict tasks, which require the child to make a response that conflicts with a prepotent response. Thus, the day-night task and Luria's hand game are considered conflict tasks (as well as complex response inhibition tasks) because they require the child to respond in a way conflicting with the natural response (i.e., associating a picture of the sun with night time and making a fist when shown fingers, respectively). Finally, Nigg (2000) distinguished several forms of inhibition that cover cognitive, behavioral, and emotional regulation.

Age differences. Garon et al. (2008) described rapid improvements in early childhood on a variety of complex response inhibition tasks (i.e., conflict tasks), such as the day-night task and Luria's hand game (see also Carlson & Moses, 2001; Hughes, 1998; Lehto & Uusitalo, 2006; Sabbagh, Xu, Carlson, Moses, & Lee, 2006). Despite their apparent similarities, different conflict tasks show different ages of mastery, perhaps indicating different cognitive demands. For Luria's hand game, which requires children to make a fist when shown a finger and vice versa, the most improvement typically occurs between ages 3 and 4 (Hughes, 1998); however, for the day-night task, 3- and 4-year-olds find it equally difficult (Carlson, 2005) and improvements may continue into middle childhood (Gerstadt et al., 1994). Furthermore, preschool children perform better on Luria's tapping task than the day-night task (Diamond & Taylor, 1996). Like Luria's hand game, the tapping task requires the inhibition and activation of hand motor responses, whereas the day-night task requires the inhibition and activation of verbal responses. In addition to different response modalities, Diamond and Taylor (1996) argue that the two tasks differ in the degree of response prepotency: There is a stronger tendency to say "day" when shown a sun than to mimic the motor movement of another person. However, evidence of a mirror neuron system that facilitates the imitation of hand gestures (e.g., Iacoboni & Dapretto, 2006)

calls into question whether inhibiting the mimicking of hand movements is necessarily easier. In any case, preschoolers have some ability, although still immature and sensitive to task demands, to override a naturally prepotent response in favor of an alternative.

The Dimensional Change Card Sort (DCCS) is another complex response inhibition task used frequently with preschool children. Rather than requiring the inhibition of a naturally prepotent response, the DCCS creates a prepotent response during the preswitch phase that must later be inhibited. The child is shown a deck of cards that vary on two dimensions—shape (e.g., rabbit vs. battleship) and color (e.g., red vs. blue). During the preswitch phase, the child must sort the cards according to one dimension (e.g., color; "If it's red, it goes here; if it's blue, it goes here"). In the postswitch phase, the child is asked to sort the cards by the other dimension (e.g., shape). Similar to other conflict tasks, reductions in perseveration occur from ages 3 through 4 (Carlson, 2005; Zelazo et al., 2003).

Manipulations of the standard DCCS provide insight into the developmental sequence of inhibition (e.g., Zelazo, 2006; Zelazo et al., 2003). In a No Conflict DCCS, the inhibitory demands are minimized, but the WM demands are maintained by presenting four nonoverlapping rules by which to sort the cards (e.g., sort by two colors at preswitch and by two shapes at postswitch). Here, 3- and 4-year-olds perform equally well, suggesting that the WM demands by themselves are not the cause of difficulty for the younger children in the standard DCCS (Zelazo et al., 2003). In an Advanced DCCS, a third sorting dimension is added; if there is a star on the card, the child should sort by color, but if there is not a star, the child should sort by shape. Five- and six-year-olds find this task difficult, showing a < 50% chance of passing (Carlson, 2005). Thus, as predicted by Zelazo's cognitive complexity and control (CCC) theory (Zelazo et al., 2003), the complexity of a task, defined in terms of the hierarchical structure of the child's rule system, is critical to task performance. The complexity of the child's rule system increases as the child integrates and embeds seemingly incompatible rules based on color and shape: "If sorting by color, the blue one goes here; if sorting by shape, the rabbit goes here." An inability to integrate the rule systems causes perseverative errors; that is, the child will continue to sort the cards based on the initial dimension—color or shape. The Advanced DCCS requires the integration of another rule based on

the presence of a star, whereas the No Conflict version does not require the integration of any rules—supporting the notion that the integration of rules is critical for inhibition development.

Findings of further improvement in inhibition after age 5 are mixed. In a rare study examining a wide age range, Klenberg et al. (2001) found improvement from ages 3 to 6 on the Statue task (maintaining a body position while the experimenter attempts to distract the child) and the Knock and Tap game (e.g., tap when the experimenter knocks and vice versa), but no further significant improvement through age 12. However, these tasks may have been too easy for the older children—perhaps because of the low prepotency of the response to be inhibited. A similar problem of finding appropriate tasks when using a wide age range is that the cognitive battery used in this study, the NEPSY, contains subtests not suitable for the youngest children. Thus, the 3- and 4-year-olds only completed 3 of the possible 12 subtests, making comparisons across the entire age range difficult. Still, in support of the conclusion that inhibition stabilizes by the early school years, Lehto et al. (2003) found no significant changes in inhibition between ages 8 and 13 on the TOL and Matching Familiar Figures tasks (although the inhibitory aspects of these tasks are not clearly identified, and see Steinberg et al., 2008, for continued improvements in an impulsivity measure of TOL performance through adolescence and early adulthood).

Other studies find further development after age 8. Interestingly, many of these studies have utilized computerized tasks such as the Go-No-Go task or the continuous performance task (CPT), both of which require a response to certain stimuli and inhibition of response to other stimuli (Brocki & Bohlin, 2004; Casey et al., 1997; Cragg & Nation, 2008; Johnstone et al., 2007; Jonkman, 2006; Jonkman, Lansbergen, & Stauder, 2003; Lamm, Zelazo, & Lewis, 2006). In the Go-No-Go computer task, the child must respond (by pressing a designated keyboard button) only to “go” stimuli (e.g., all letters except X) and inhibit response to the “no-go” stimulus (e.g., the letter X). The CPT adds a cue prior to go and no-go stimuli. For example, the child may be asked to respond to the letter X, but only when preceded by the letter A. Thus, responding to a no-go stimulus is considered a failure of inhibition (“commission errors”). Unlike conflict tasks, these tasks do not require the execution of an alternative response.

In one of these studies (Brocki & Bohlin, 2004), significant improvements occurred from ages 7 to 9

to 11 on behavioral measures that loaded onto a factor that the authors labeled a “disinhibition” factor (CPT disinhibition, CPT impulsivity, CPT inattentive impulsivity, and Go-No-Go commissions). Likewise, both Jonkman et al. (2003) and Casey et al. (1997) found significant decreases in commission errors on these tasks between age 9 and young adulthood (see also Jonkman, 2006; Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004). Cragg and Nation (2008) used a modified Go-No-Go task in which children had to depress a home key prior to pressing a target key. This modification allowed for partial commission errors (depressing of home key but not pressing target key in response to the no-go stimulus) in addition to traditional commission errors. In comparing 5- to 7-year-olds with 9- to 11-year-olds, only the partial commission measure was sensitive to developmental change, revealing that older children were able to inhibit a motor plan (releasing the home key and pressing the target key) at an earlier stage of execution than younger children. Johnstone et al. (2007) also found that the traditional no-go commission error was insensitive to change from ages 7 to 12. In contrast, they did find that performance on a Stop-Signal task, during which the child must inhibit a currently activated response, was sensitive to change across this age span. Thus, these two studies suggest that the stage of execution is a factor in inhibition difficulty: Terminating an already executed response appears to be more difficult than inhibiting a response that has yet to be executed or is in an earlier stage of execution.

In a computerized anti-saccade task (Fischer, Biscaldi, & Gezeck, 1997; Munoz, Broughton, Goldring, & Armstrong, 1998), children fixate on a central target. The target is turned off and a peripheral cue is turned on. Children are told not to look at the target but instead to look to the opposite side. Thus, any initial glance toward the cue is an inhibitory failure. Dramatic improvement in both reaction time and accuracy during the grade school years is followed by slower improvement during early adolescence. Similarly, Williams, Ponesse, Schachar, Logan, and Tannock (1999) found improvement up through age 12 on a “stop-signal reaction time” task, involving inhibition of a response (key press) to stimuli when a tone sounds. Moreover, Huizinga et al. (2006) found continued improvement in both reaction time and accuracy measures on the Stop-Signal task and Eriksen Flankers task until age 15 and on a Stroop-like task (inhibiting saying a color word in order to state its

conflicting font color) until age 21. Finally, adults, more than adolescents, appeared aware of making an inhibition error as they momentarily slowed their response for the next trial in order to prevent further error (Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005), which suggests the contributions of metacognitive development even after adolescence.

The fact that several studies have found improved performance beyond early childhood on ostensibly simple response inhibition tasks (e.g., anti-saccade task)—or at least on tasks (e.g., Go-No-Go task) simpler than conflict tasks—challenges the notion that performance on these tasks matures early on. For example, the computerized Go-No-Go task should be easier than Luria's hand game because it requires only response inhibition of a prepotent response rather than response inhibition followed by the execution of an alternative response. One explanation for this involves how task performance is measured. Computerized tasks contain multiple trials and measure reaction time very precisely (to the millisecond), thus increasing sensitivity to subtle changes. Alternatively, since many of these studies with older children have utilized computer-based tasks, perhaps some of the age-related improvements are related to computer-specific abilities (e.g., more efficient use of keyboard or mouse).

In summary, the first leap in attaining inhibition appears in the preschool years. By age 4, children show signs of successful performance on both simple (i.e., pure response inhibition) and complex inhibition tasks (i.e., response inhibition plus alternative response). By the same age children can operate on a bidimensional card by one dimension and then inhibit that to use the second dimension (i.e., successfully perform DCCS). Inhibition continues to improve, particularly from age 5 to 8 (Romine & Reynolds, 2005) and particularly for tasks that combine inhibition and WM (Carlson, 2005; Gerstadt et al., 1994), but also at later ages, especially on computerized tasks. Unlike the early improvements, these are unlikely to be fundamental changes in cognition (e.g., like preschoolers' acquisition of the rule-formation ability needed to perform the DCCS). Instead, refinements seem to involve quantitative improvements in accuracy, perhaps due to an increasing efficiency to override prepotent responses. Thus, it may be that inhibition tasks have varying sensitivities, with some being sensitive to the conceptual gains in early childhood and others being sensitive to the refinements in strength of the relevant cognitive skills or the gen-

erality of application in later childhood and even adolescence. These sensitivities seem to be determined by a number of factors including how performance is measured, the response modality, the strength of the response bias, the stage of response execution, and the degree of simultaneous WM demands imposed by the task.

Evidence from neuroscience. One method to examine the neural response underlying response inhibition is to measure the brain's electrical activity via electroencephalogram (EEG). Measuring during infancy, early childhood, and middle childhood, one longitudinal EEG study (Bell, Wolfe, & Adkins, 2007) reported qualitative change in brain activity underlying complex response inhibition—measured by WM and inhibitory control tasks. At 8 months of age, correct performance on the A-not-B task was associated with increased global cortical activity, whereas at age 4½, day-night performance was associated only with increased medial-frontal activity. By age 8, this activity became even more focused in the right frontal scalp regions during completion of the WCST. This shift from global to localized activity during task completion may signal the growing efficiency of the brain and the growing functionality of the PFC for complex response inhibition.

EEG studies with older children indicate continued localization of brain activity from middle childhood to adulthood. Looking closely at frontal activity, Jonkman (2006) found a linear increase in no-go P3 amplitude (a positive wave 300–500 ms after stimulus presentation) across development: Children aged 6–7 showed no P3 activity, children aged 9–10 showed limited P3 activity in frontal-central electrodes, and young adults showed broad P3 activity across frontal and frontal-central electrodes (see also Jonkman et al., 2003). P3 activity has been interpreted to index the allocation of attentional resources during stimulus engagement, with greater activity representing greater resource allocation (Polich, 1987). In contrast, the no-go N2 response (a negative wave 150–400 ms after stimulus presentation) decreased across the same age span, with the largest decrease in amplitude occurring between ages 6 and 10. The N2 response is thought to indicate conflict monitoring, needed when the prepotent response conflicts with the task-required response. The decrease in the N2 response may indicate that compensatory mechanisms are present in younger children and that the task induces less conflict with increasing age (Jonkman, 2006).

Similar findings come from Lamm et al. (2006) who reported decreases in frontal N2 amplitudes

from ages 7 to 17 on no-go trials, which they attributed to increasing neural efficiency that may result from the regressive neural changes described above (e.g., synaptic pruning). As evidence that frontal N2 activity reflects conflict monitoring and inhibition, performance on tasks requiring conflict monitoring and inhibition (the Stroop task and Iowa Gambling Task) predicted decreases in frontal N2 amplitudes beyond that predicted by age. As further support, Johnstone et al. (2007) observed stronger frontal N2 activity in response to no-go stimuli than go stimuli. However, they found no change in the ability to inhibit no-go responses across the ages of 7–12. Moreover, what age-related changes in brain activity the authors did observe were found in nonfrontal brain regions—including decreases in central and parietal N2 amplitude—suggestive more of refinements in stimulus processing than in the inhibition response per se. All together, these EEG studies provide evidence that inhibition development is paralleled both by increases and decreases in neural activity, perhaps indicative of progressive and regressive neural change.

Researchers also have used neuroimaging assessments, such as fMRI, to document the increasing efficiency of the neural response underlying response inhibition. On the Go-No-Go task, Casey et al. (1997) observed no difference in the *location* of activation in the PFC between children ($M_{\text{age}} = 9.92$) and young adults but did measure *greater volume* of activation in children during the no-go condition, particularly within the dorsal and lateral PFC. Moreover, a longitudinal imaging study (Durstun et al., 2006) reported that activation within the PFC only increased from ages 9 to 11 for specific prefrontal regions (ventral PFC) correlated with task performance. In contrast, activity within prefrontal regions uncorrelated with task performance (dorsolateral PFC) decreased with age. Similar to the explanation offered by Lamm et al. (2006), Casey et al. and Durstun et al. (2006) suggested that the greater activation in children may correspond to inefficiency in the inhibition mechanism and that neural development is characterized by increased localization of activity to brain regions directly linked to the behavioral response and decreases in activity in supplementary brain regions.

One structural imaging technique, diffusion tensor imaging (DTI), measures the myelination of axons. Myelinated axons transmit signals more efficiently and rapidly than unmyelinated axons. Liston et al. (2006) measured myelination in participants aged 7–31, who also performed a Go-No-Go task and found that myelination of projections from

the PFC to the striatum increased with age and correlated with no-go task performance. Importantly, myelination of corticospinal axons also increased with age but did not correlate with task performance. Thus, the increasing myelination of frontostriatal connections, in particular, across childhood and adolescence seems to underlie the maturation of response inhibition.

A synthesis of these neuroscience studies does not suggest a one-to-one correspondence between changes in brain activity and changes in task performance. Instead, task performance often changes subtly, if at all (e.g., Johnstone et al., 2007), whereas the pattern of neural activity may change dramatically. It seems that school-age children can successfully complete response inhibition tasks (with concurrent WM requirements or not) but, in doing so, enlist a more global pattern of activation than they will later on. With development comes localized and efficient activation in specific PFC regions (e.g., ventral PFC) pertinent to task completion. These dramatic changes in neural activity may translate into only subtle improvements in response inhibition, such as greater efficiency and less effort.

Developmental issues. Several developmental issues about inhibition need to be examined further. First, by what process does a child move from one level (e.g., simple inhibition of a response) to another level (e.g., the development of a more complex rule that controls two responses)? Does the former contribute to the development of the latter? Would examining the transition period yield clues to the qualitative and quantitative aspects of this change? Second, what is the form of the developmental trajectory from age 3 to adolescence? Is development linear? This question is difficult to answer because of the difficulty of finding appropriate tasks for a large age span. The dramatic improvement from ages 3 to 5 appears to be followed by less dramatic change from 5 to 8 and even less change after age 8 (although brain maturation continues). However, the tasks used with younger children likely have different inhibitory requirements than those used with older children. In a meta-analysis of EF studies from age 5 to adulthood, Romine and Reynolds (2005) found the greatest advancements in inhibition of prepotent responses from ages 5 to 8. A meta-analysis that includes younger children is greatly needed to clarify the rate of change from the preschool to grade school years.

Relevant to this apparent developmental trajectory is the problem of task impurity. Inhibition appears not to be a uniform construct. For example,

interference control, cognitive inhibition, and motor inhibition may be distinct processes tapped by different tasks and develop at different rates across childhood (Nigg, 2000). Furthermore, classic tasks of inhibition utilize cognitive components in addition to inhibition. As already mentioned, many tasks also have significant WM requirements. For another example, performance on the Stroop task may depend not only on the ability to inhibit reading a color word in order to read its actual color but also on the child's level of reading automaticity (Leon-Carrion, García-Orza, & Pérez-Santamaría, 2004). As a result, performance, measured in terms of reading errors, does not improve in a linear fashion, but rather forms a quadratic relation: There is an initial increase in reading errors from ages 6 to 10, followed by a dramatic decrease in errors through age 17. This suggests that as word reading becomes more and more automatic from ages 6 to 10, inhibition of that process to say the color becomes more difficult, which negatively affects reading accuracy. Afterward, the inhibition mechanism needed may be mature enough to compensate for this reading automaticity. Thus, this developmental trajectory may have as much to do with developing reading automaticity as with developing inhibition. A similar careful analysis of other inhibition tasks might reveal similar complexities regarding the question: "What develops?"

Adding further complexity, social factors likely influence inhibition performance. For example, there is evidence for a developmental regression in self-regulation in early adolescence (Anderson, 2002), particularly as evidenced by increased risky behavior during this time (Steinberg, 2007). One perspective suggests that the interaction of a mature socioemotional network (involving mainly limbic structures) and an immature EF-related control network within a context of increased peer pressure leads to adolescents' increased risk taking (Steinberg, 2007). This perspective suggests that outward regressions may occur not so much because there are actual regressions in inhibition per se but because exposure to emotionally laden and risky situations increases at this point in development when inhibition is still immature.

Summary. Regarding the first component in the Miyake et al. (2000) model, cognitive, behavioral, and brain assessments generally show rapid early improvements in inhibition followed by slower improvements through adolescence, along with greater brain localization throughout childhood and adolescence. Mechanisms of development may

include brain maturation, increased ability to handle task complexity, increased ability to use rules, and emerging metacognition.

Working Memory

Like inhibition, WM research has been complicated by various definitions of the construct, as well as (and perhaps resulting in) the use of differing assessment tasks. In general, WM involves the ability to maintain and manipulate information over brief periods of time without reliance on external aids or cues (Alloway, Gathercole, & Pickering, 2006; Goldman-Rakic, 1987; Huizinga et al., 2006). Neuroimaging research suggests that WM tasks vary by how much the task elicits PFC activity; consequently, researchers suggest that WM tasks vary in the degree to which they require "executive control" (Luciana et al., 2005). That is, more complicated WM tasks that require the maintenance and manipulation of information in order to direct behavior toward future goals (e.g., backward digit span, delayed-response tasks, self-ordered searches) ostensibly rely on more executive involvement (and consequently more PFC activity; D'Esposito & Postle, 1999) than simpler WM tasks that require only the maintenance of information (e.g., forward digit span). Accordingly, the rate and form of WM development will hinge upon the degree to which a task requires executive processes.

Gathercole, Pickering, Ambridge, and Wearing (2004) invoked the classic WM model of Baddeley and Hitch (1974) to distinguish between executive WM tasks and online storage tasks. According to Gathercole et al., executive WM requires that either the verbal storage system (i.e., the phonological loop) or the visuospatial storage system (i.e., visuospatial sketchpad) work in concert with a coordinating central executive. Simple WM tasks require little input from the central executive but rely solely on either the phonological loop (e.g., forward digit recall) or visuospatial sketchpad (e.g., visual pattern recall). Complex tasks (e.g., backward digit recall), on the other hand, may require that multiple WM tasks be performed concurrently, and therefore the central executive must coordinate those processes. This tripartite model was supported by a CFA of children aged 6–15 on a battery of verbal WM, visuospatial WM, and executive WM tasks, which suggests the differentiation of the WM subsystems by early grade school.

Age differences. A variety of tasks document improvement in WM during the preschool years (see Garon et al., 2008). Gathercole et al. (2004)

reported that by age 6, the executive component of WM is sufficiently developed to be used during complex tasks that require coordination of WM subcomponents. In addition, the same researchers found that simple and complex WM tasks had similar developmental trajectories—a linear increase from ages 4 to 14 and a leveling off between ages 14 and 15 across nearly all tasks examined. Luciana et al. (2005), drawing on a battery of nonverbal tasks, found that the developmental course of WM depends on the complexity and, thus, the executive demands, of the task, with less demanding tasks being mastered earlier in development. Their battery of nonverbal tasks ranged from a nonverbal face recognition task (lowest executive demand) to a spatial self-ordered search (highest executive demand). The former simply required the child to maintain a facial representation over a delay in order to discriminate a previously viewed face from a novel one, and performance was unchanged between ages 9 and 20. The latter task required the child to search varying locations on a computer screen for hidden tokens, to remember locations where a token was found, and to strategically explore other locations, and performance continued to improve until age 16.

Extending the work of Luciana et al. (2005), Conklin et al. (2007) used a battery of verbal and spatial WM tasks across the ages of 9–17. Across age, children tended to perform better on the spatial versus verbal WM tasks, even though the tasks were thought to tap similar cognitive processes (e.g., strategic self-organization). Still, the developmental trajectories were similar for verbal and visuo-spatial WM tasks, and instead, differed based on task complexity. In agreement with the conclusions of Luciana et al., Conklin et al. suggest that the age of mastery depends more on the degree of *processing* (with more complex tasks requiring a greater degree of processing) rather than the *content* to be processed (e.g., verbal vs. visuospatial material).

One problem, although, with this use of different tasks to manipulate the executive demands on WM is that it is difficult to ensure that non-EF processes are equivalent across tasks and that they do not influence age differences in performance. Luciana and Nelson (1998) addressed this important issue by employing only a self-ordered search task, which varied over trials in the executive demands, based on the number of locations (2–8) the child may search for tokens. By increasing the number of search locations, greater demands are placed on the executive components of WM to search strategically and to avoid previously searched locations by

continually updating WM. Similar to the findings of Luciana et al. (2005), for the least demanding condition, performance was equivalent among children aged 4–8, adolescents, and young adults. However, as the number of search locations increased, age differences emerged. For three locations, performance maturity was reached at age 6, for four locations, maturity was not reached until adolescence, and for six and eight locations, improvements continued until adulthood. Thus, the development of executive WM occurs gradually with continued refinement through adolescence, especially for tasks that require the maintenance and manipulation of multiple items.

Evidence from neuroscience. In accord with the behavioral results, fMRI evidence points to a protracted developmental course leading to localized activity within the PFC during WM functioning. Kwon, Reiss, and Menon (2002) reported a quantitative linear increase in activity within a frontoparietal network, including ventral and dorsal regions of the PFC, from ages 7 to 22 while performing a visuospatial WM task (*n*-back task). The authors note that the increased activity within right-lateralized dorsal PFC likely subserves the maturation of visuospatial attention and executive processes, whereas the increased activity within a left-lateralized frontoparietal network subserves the maturation of a phonological rehearsal system. Increases in this neural activity were related more to age than to task performance (accuracy and RT). Thus, with a dramatic and prolonged increase in specialization of the WM neural circuitry through childhood and adolescence comes only limited overt task improvement, especially during adolescence.

Scherf, Sweeney, and Luna (2006) reported both qualitative changes (location of activation) and quantitative changes (amount of activation) in the neural response underlying visuospatial WM from childhood ($M_{\text{age}} = 11.2$) through adulthood ($M_{\text{age}} = 29.5$). During childhood, activation occurred in qualitatively different premotor regions and also in the lateral cerebellum, which was absent in later development. Also during childhood, there was quantitatively greater activity in ventromedial regions, including the thalamus and basal ganglia. Adolescence ($M_{\text{age}} = 15.7$) brought a shift in activity to frontal regions, including the right dorsolateral PFC. Finally, from adolescence to adulthood, activity became more localized and lateralized as left dorsolateral PFC activation increased and right dorsolateral PFC activation decreased. Moreover, activity increased substantially in the

anterior cingulate (described as qualitative change by the authors). The end result of these changes (quantitative and qualitative, progressive and regressive) from childhood to adulthood is a functionally specialized visuospatial WM neural network (see Klingberg, Forssberg, & Westerberg, 2002, for similar changes from ages 9 to 18 on a visuospatial WM task).

Increased WM also correlates with structural neural indices, such as the maturation of white matter (i.e., the myelination of neuronal axons), measured by DTI. Nagy, Westerberg, and Klingberg (2004) reported that the development of visuospatial WM from ages 8 to 18 correlated with myelination in regions primarily of the frontal lobe close to the parietal lobe (superior and inferior left frontal lobe), whereas the development of reading ability correlated with myelination in the left temporal lobe. Thus, during late childhood and adolescence, the maturation of specific cognitive functions is linked to the maturation of specific neural circuits, rather than to global brain maturation.

Developmental issues. One developmental issue concerns the developmental relation between WM and inhibition. It seems that many inhibitory tasks, particularly complex ones, also place demands on WM (Bell et al., 2007; Garon et al., 2008; Simpson & Riggs, 2005), and the combination of the two within a single task poses significant difficulty for young children (e.g., Carlson, 2005). For example, in the day-night task the child must maintain the rule in WM. However, research also suggests their independence. If the inhibitory component is eliminated on this task, the difference between 3.5- and 5-year-olds nearly disappears (Simpson & Riggs, 2005), which suggests that it is inhibition, not WM, that causes the age difference. (It is also possible that eliminating the WM component also would reduce the age differences, which would suggest that the interaction of the two components is important.) Similar outcomes were found with a Stroop-like task, a CPT task, and a start-stop task (Beveridge, Jarrold, & Pettit, 2002), as well as the DCCS (Zelazo et al., 2003). Thus, relevant to the Miyake et al. (2000) model, it appears that WM and inhibition are largely separate constructs (for a counterargument, see Bell et al., 2007; Davidson et al., 2006). That said, many tasks described as either WM or inhibition tasks likely place demands on both types of processes (e.g., the day-night task), and therefore, it is difficult to obtain a pure measure of one or the other.

Summary. Performance on complex WM tasks (i.e., those tasks requiring a greater degree of

processing such as the maintenance and manipulation of information) improves at least through adolescence. Like the development of the neural circuitry subserving response inhibition, the development of the WM circuitry involves progressive and regressive changes, resulting in a localized pattern of activity within a frontoparietal network, including the DL-PFC. Unlike the trajectory of inhibition development that shows large improvements during the preschool years followed by more modest, linear improvements through adolescence, most of the evidence suggests that the trajectory of WM development is linear from preschool through adolescence.

Shifting

The third core EF is the ability to shift between mental states, rule sets, or tasks (Miyake et al., 2000). There appears to be substantial need for inhibition and WM processes for shifting. Reminiscent of the cognitive processes associated with inhibition tasks (e.g., DCCS), Miyake et al. (2000) suggest that shifting may “involve the ability to perform a new operation in the face of proactive interference or negative priming” (p. 56). It would seem, then, that the ability to inhibit previously activated mental sets would be important for successful shifting and that perseverative errors (i.e., continued responding based on the previous mental set) would indicate shifting failures (Anderson, 2002). The typical distinction between tasks deemed “inhibition tasks” and those deemed “shifting tasks” is that the latter typically rely on switching between two or more mental sets—with each set possibly containing several task rules—rather than the inhibition of a single response (Crone, Somsen, Zanolie, & Van der Molen, 2006). Moreover, in tasks of inhibition, the rules are usually explicitly expressed rather than implied through either negative or positive feedback. Thus, the DCCS with its explicit indication of set change is often categorized as an inhibition task (but see Garon et al., 2008, who classify the DCCS as a shifting task). Shifting tasks also place demands on WM by requiring the maintenance and updating of that mental set based on feedback.

Age differences. The ability to shift improves with age (Anderson, 2002; Cepeda, Kramer, & Gonzales de Sather, 2001; Crone, 2007; Crone et al., 2006; Garon et al., 2008; Somsen, 2007). Preschoolers, aged 3–4, can successfully shift between two simple response sets in which the rules are placed in a story context (Hughes, 1998) or when demands on inhibition are reduced (Rennie, Bull, &

Diamond, 2004). For example, in a simplified version of the WCST (Hughes, 1998), preschoolers can determine what a teddy bear's favorite shape is, based on feedback, and then after a set shift they can decide what a second teddy bear's favorite color is, based on differing feedback.

As previously mentioned, Senn et al. (2004) reported that whereas inhibition and WM were interrelated and predicted complex task performance (i.e., TOH), shifting was unrelated to inhibition, WM, or TOH performance in preschoolers. Accordingly, the authors suggest that shifting may not be differentiated from WM and inhibition—and therefore, is less developed—at this age. This is sensible given that inhibition and WM processes seem to be prerequisite processes for successful shifting. As Garon et al. (2008) noted, before children can successfully shift between response sets, they must be able to maintain a response set in WM and then be able to inhibit the activation of a response set in order to activate an alternative one.

More complex tasks show further development in older children and adolescents. Luciana and Nelson (1998) utilized a set-shifting task that progressed through nine stages of increasing difficulty and complexity (the intradimensional–extradimensional set-shifting task from the CANTAB). This is a fruitful strategy as it shows exactly how complex a set children can handle at each age, thus permitting comparisons across a wide age range. This task required children to respond correctly, based on previous feedback, to either lines or shapes presented on a computer. Children had to attend to feedback, infer the correct rule at that moment, and respond accordingly. At set points, reinforcement switched such that the correct response (e.g., shapes) switched to the opposite of what was previously correct (e.g., lines). The main improvement occurred from ages 5 to 6, at Stage 7, in which the rule did not switch (i.e., between lines and shapes), but the examples of lines and shapes did change. For successful completion of this stage, children needed to utilize feedback from previous stages to shift their response to new examples of either lines or shapes. With increasing age up through young adulthood, there was a steady increase in the proportion of subjects who completed all nine stages of the task, indicating that shifting ability continues to improve over many years.

Huizinga et al. (2006) investigated set shifting on three computerized tasks in which a cue signaled to which dimension the child should respond. Sporadically, the cue would switch, indicating a set shift. "Shift cost" was the difference in response

time between shift trials and nonshift trials. The shift cost for the 7- and 11-year-olds was significantly greater than for the 15-year-olds, who did not differ from the young adults ($M_{\text{age}} = 20.8$). Thus, shifting reached adult-like levels around age 15. Similarly, Davidson et al. (2006) found improvement from age 4 through adolescence. Interestingly, they found different developmental trajectories for the switch cost for accuracy versus reaction time. Whereas the shift cost to accuracy diminished through early adolescence, the switch cost to reaction time increased until adulthood. This speed–accuracy trade-off indicates that with increasing age, participants were more likely to slow down their responses on shift trials to ensure that they were responding accurately. Thus, improved metacognition—knowing that slowing helps performance and being able to detect when it is advantageous to do so—may be one mechanism of developing accurate set shifting. This design, examining developmental curves on two or more measures, is a model for how future research could tease apart aspects of an EF component and tell a more nuanced developmental story.

Evidence from neuroscience. In further support of the role of metacognition, especially monitoring and changing one's own performance, Crone et al. (2006) measured heart rate changes during a task shifting paradigm, in which the child "opened" doors on a computer screen in order to help a computerized donkey find its way home. Heart rate slowing following negative feedback (indicated by a negative sign after opening an incorrect door) would indicate a realization of an error and the evaluation of the current set rules. For ages 8–18, heart rate slowed to a similar degree following the unexpected feedback that occurs immediately after a task shift. The difference between the age groups occurred only in errors that continued after receiving feedback for a task shift. Following such an error, the 8- to 10-year-olds did not show heart rate slowing as much as the 12- to 14-year-olds or the 16- to 18-year-olds. Thus, although younger children could detect a task shift as well as older ones, they did not detect performance errors after the shift as well. Somsen (2007) reported that on a computerized WCST an increase in attention to feedback about errors predicted performance in adolescents, but not younger children, which again supports the role of metacognition, particularly being able to use feedback to change one's behavior.

fMRI analyses implicate neural activity within multiple regions of the PFC and elsewhere as

shifting develops. Rubia et al. (2006) reported increased activation in inferior frontal, parietal, and anterior cingulate regions, but decreased DL-PFC activation across adolescence during shifting. They proposed that the increased activity in the anterior cingulate cortex (ACC) reflects the maturation of conflict monitoring processes, whereas the increased DL-PFC activation in younger participants reflects compensatory neural activity—quite similar to the explanation offered by Casey et al. (1997) regarding Go-No-Go performance.

Also focusing on conflict monitoring, Crone (2007) suggested that other regions may underlie the growing ability to monitor and change one's performance. During development, adult levels of processing feedback about performance on a shift task are reached first for the medial PFC (important for violations of processing expectations), and then for the left dorsal PFC (important for hypothesis testing and seeing the need for adjustment of behavior). The first development occurs between ages 8 and 10 and adolescence and the second between adolescence and adulthood. Thus, because cognitive shifting requires the child to switch between multiple response sets based on feedback, neural networks involving the ACC and regions of the PFC that are responsible for monitoring and detecting conflict (e.g., performing a response and receiving negative feedback) seem to be critical to successful shifting.

Developmental issues. A useful approach for pinpointing exactly *what* changes with age on a shifting task is to break such a task down into component processes and examine neural correlates of age changes in these processes. A recent interesting study (Morton, Bosma, & Ansari, 2009) examined separately two processes in the DCCS task: (a) rule switching (e.g., switching from color- or shape-based sorting) and (b) detection and resolution of conflict when stimuli can legitimately be sorted in two ways (color or shape). Rule switching showed fMRI activity in the lateral PFC and posterior parietal cortex in both children and adults. Most interesting, however, was an interaction of rule switching and age in these regions. Rule switching modulated activity in the left posterior parietal cortex and right middle frontal gyrus in adults but not in children. Thus, the networks involved in switching presented a qualitative developmental change from childhood to adulthood. Although the age-related results were less clear for conflict processing, they showed that conflict processing and rule switching are separable processes that, when considered separately, can give a more

fine-grained analysis of age-related neural and behavioral changes on the DCCS task.

Age-related improvements in shifting also occur through the development of processes other than shifting per se. For example, the ability to generalize a rule set to a novel set of stimuli facilitates shifting performance (Luciana & Nelson, 1998). The abilities to maintain the new rule set and to detect performance errors after a successful shift also are important (Crone et al., 2006). Finally, the development of metacognitive strategies, such as slowing down responses to preserve a high level of accuracy, enhances accurate shifting (Crone et al., 2006; Davidson et al., 2006).

Summary. The ability to successfully shift between task sets follows a protracted development through adolescence. It appears that preschool-aged children can handle shifts between simple task sets and later can handle unexpected shifts between increasingly complex task sets. Both behavioral and physiological measures indicate that during adolescence, monitoring of one's errors is evident, and by middle adolescence, task switching on these complex shift paradigms typically reaches adult-like levels. Because of greater need for multiple cognitive processes, mature shifting likely involves a network of activity in many PFC regions.

Conclusions About Development and Directions for Future Research

Developmental Trajectories

It is clear that previous reviews of EF in children, mainly focused on preschoolers, leave out much of the story of the development of EF and limit the search for sequences and mechanisms of development. There is substantial further development in all components after age 5, and even through adolescence (see Best et al., 2009). Including broader age ranges provides information about developmental trajectories. Results are inconsistent, but inhibition appears to show particularly striking improvement during the preschool years and less change later on. WM shows more gradual linear improvement throughout development, as does shifting. These different trajectories provide support for the Miyake et al. (2000) position that the three components are somewhat diverse. However, the differing trajectories extend the Miyake et al. model by suggesting that the degree of unity or diversity of EF varies from age to age.

The evidence suggests both quantitative and qualitative EF development. Much of the change

appears to be quantitative and gradual, although the change may be more rapid in the early years. In many relevant brain regions, activity decreases with age, perhaps reflecting the growing efficiency of the neural response. Some change appears to be qualitative, suggesting changes in brain organization as the site of brain activity shifts during development (e.g., Scherf et al., 2006). In other regions, activity seems to increase—for example, in the ventral PFC during response inhibition and in the DL-PFC during WM. As Olson and Luciana (2008) note, the discrepant behavioral trajectories along with this segregation of activity tentatively suggest that different regions of the PFC support different EFs. Thus, regional differences in the course of neural development may be responsible for different developmental trajectories of response inhibition, WM, and shifting. The emergence of metacognition may also bring qualitative change when children learn to use feedback about errors to change their approach to the task.

It is important to note that despite evidence for the functional differentiation of the PFC, there also seems to be activation of common regions during the completion of distinct EF tasks. This may in part be due to EF task impurity—notably the fact that it is difficult to tease apart WM and inhibitory processes (Roberts & Pennington, 1996) and that shifting likely builds on WM and inhibitory processes (Garon et al., 2008). Additionally, it may indicate the common processes that underlie the various EF components, that is, the “unity” aspect of the “unity and diversity” of EF (Miyake et al., 2000). Exactly how EF is instantiated in the brain, including to what degree the PFC is functionally differentiated, continues to be a debated issue (Olson & Luciana, 2008).

Several task-related factors also influence the observed developmental trajectory of a latent EF component. One is the degree of task complexity, with better success expected on simpler tasks. Task complexity can be manipulated in several ways, but notably by increasing the degree of response prepotency in inhibition tasks (Diamond & Taylor, 1996) or by increasing the degree of “working” with information in WM tasks (Luciana et al., 2005). Thus, a simple response inhibition task should be easier than the Stroop task, and a WM task that requires online storage should be easier than one that requires information manipulation. A second is how performance is measured (e.g., partial vs. full commission error on the Go-No-Go task; Cragg & Nation, 2008). A third is the response modality (e.g., bodily vs. verbal response; Diamond

& Taylor, 1996). Thus, researchers need to consider carefully how these task factors may shape the developmental trajectory of constructs ostensibly measured by such tasks. Moreover, the influence of these task factors suggests caution in drawing strong conclusions about the development of EF.

Mechanisms of Development

Research needs to move beyond a focus on description—the ages at which the EF components emerge, show rapid development, and reach maturity—and address mechanisms of development. How do children move from early to later levels of competence within an EF component, for example, inhibition? Does the early phase of development of one component facilitate the development of other components? The developmental relations between components of EF could be examined by research designs that include assessments of several components of EF together in the same study, at different ages. The comparison of trajectories of several EF components can suggest mechanisms of development. For example, the early rapid improvement in inhibition may contribute to the later developments of shifting and planning.

Promising designs. Several designs used by studies reviewed here seem particularly promising for examining mechanisms of development within or between components: (a) Use meta-analyses (Romine & Reynolds, 2005) to examine the effects of moderating variables at different ages by including a larger age range. (b) Compare the developmental trajectories for two or more aspects of performance (e.g., speed and accuracy, Davidson et al., 2006; Baker, Segalowitz, & Ferlisi, 2001; number of moves, amount of planning time prior to making the first move, and the proportion of perfect solutions on the TOL task, Huizinga et al., 2006) for clues as to whether one aspect influences another. (c) Look for correlations between a measure of neural activity and EF performance (e.g., Morton et al., 2009). Brain maturation could permit, and thus serve as a developmental mechanism for, more advanced EF behavior, or the latter behaviors could cause changes in neural networks.

Another promising, yet rarely used, approach is to focus on the transition phase from one developmental level to the next. An example is the change from the simple rule necessary for inhibition on simple conflict tasks to the more complex rules necessary for inhibition on the DCCS task. The microgenetic method is particularly useful in this regard. In this method, children have multiple trials

on the same task or similar tasks, typically in several sessions over several weeks, and trial-to-trial changes are examined. Using this method, McNamara, DeLucca, and Berg (2007) tracked detailed change in the type of strategy used with increased experience on the TOL task. Potentially a microgenetic design could show that rapid change in one component is subsequently followed by rapid change in another component, suggesting a possible causal relation.

Microgenetic studies could be particularly useful for examining what happens at the point of shifting on shift tasks, given that several studies have observed changes that suggest metacognitive processes at work on the trials after the shift (e.g., Crone, 2007; Crone et al., 2006). In a task similar to shift tasks (DeMarie-Dreblow & Miller, 1988) when young children have to shift from one category (e.g., animals) to another category (household items) on a selective memory task, their previously effective strategy of attending to only relevant items transferred successfully to the new category but temporarily became ineffective at facilitating recall of the relevant items in this newly relevant category. Such fine-grained assessments of microgenetic changes in behavior would be particularly powerful if combined with neuroimaging assessments that track changes in brain activity at the point of behavior change.

Training studies also are useful for examining possible mechanisms of development. These can look at short-term change by (a) training one EF component and then assessing any immediate changes in other components, or (b) providing particular experiences, such as metacognitive instruction, and observing any facilitation of EF.

Training studies also can examine mechanisms over longer periods of time. The most powerful assessments of developmental mechanisms would track changes in both cognitive performance and brain organization, thus providing a multilevel assessment of influences. Such studies are rare. One such line of investigation showed both improved EFs and change in fMRI patterns of brain activity associated with EF after a 3-month after-school high-intensity exercise program for ages 7–11 (Davis et al., 2007, in press). In comparison to a control group, the exercise group had increased bilateral PFC activity and reduced bilateral posterior parietal cortex activity during an inhibition task. Another study (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005) reported evidence that 1 week of training on a computerized program centered on executive attention led to a more mature

EEG response to an inhibition task (modified flanker task) and to small, although often insignificant, behavioral improvements on the inhibition task and on a generalized intelligence test.

Finally, a powerful approach to identifying developmental mechanisms underlying changes in EF would be to study whether the cognitive, biological, and social correlates of EF change from one age to another (see Best et al., 2009, for a discussion of the social correlates of EF). This is particularly important because different processes may contribute to the development of EF at different ages.

Developmental sequences. Another good starting point to search for possible mechanisms of development is to examine developmental sequences underlying the emergence of each EF component (for a description of types of developmental sequences, see Flavell, 1972). Observed developmental sequences can suggest how early cognitive skills might be related to later ones. For example, does the development of a more advanced inhibitory ability *supplement* earlier inhibitory ability (i.e., an “addition” sequence), for example, by strengthening it, adding the ability to select an alternative response to the ability to inhibit the prepotent response, or adding metacognitive skills? Or does a more advanced, integrated inhibition skill *replace* earlier forms of inhibition, as suggested by the evidence of brain reorganization (e.g., the loss of compensatory activation with development) correlated with more advanced inhibition? In this qualitative change, the old brain organization associated with simple inhibition may no longer exist. The microgenetic design mentioned above could address supplementing versus replacing by showing whether Skill A continues to be used even after Skill B emerges.

A similar analysis of sequences and possible mechanisms could also address how the various EF components are related developmentally. That is, some EF components may facilitate the development of other EF components. For example, as WM and inhibition seem to develop ahead of shifting (Davidson et al., 2006), perhaps a certain level of WM and inhibition has to be developed before children can use them toward the development of shifting behaviors (Garon et al., 2008). Two EF components may even be mutually facilitative, as each bootstraps the development of the other in a back-and-forth fashion. Garon et al. (2008) suggested that the emergence of the three components in the first 3 years of life may be followed by an integrative period in which they become coordinated. In short, a greater emphasis on detecting possible

developmental sequences will allow for a clearer and more detailed understanding of the developmental trajectories of EF components as well as the developmental relations between those components. Finally, attention to sequences can clarify some of the differences among theories of EF development in how conflicting representations are resolved. For example, in Zelazo's CCC theory (Zelazo et al., 2003), two rules are integrated to produce a new overarching rule system. In contrast, in Munakata's (2001) theory, latent representations are maintained, even after active representations strengthen and override latent ones.

Two articles have attempted to extract developmental sequences. Anderson (2002) inferred the following sequence of EF components from an integrative review: attentional control (e.g., inhibition), information processing (e.g., processing speed), cognitive flexibility (e.g., switching), and goal setting. Romine and Reynolds (2005) inferred sequences from the age at which performance leveled off, based on a meta-analysis of ages 5–22 and average effect sizes of age-related change in performance. They found the following sequence: inhibition of perseveration, set maintenance, design fluency, planning, and verbal fluency.

One design for detecting sequences, rarely used in this research area, is to give children slightly different versions of the same task (to try to equate task demands, such as verbal demands and content area), with each task assessing a different component of EF (see Wellman & Liu, 2004, for the successful use of this design for assessing the acquisition sequence for theory-of-mind tasks). If task demands, other than the EF component of interest, are in fact equated, the mean performance on each version or the percent of children who pass each version suggests the order in which the components of EF are acquired. Also, a scalogram analysis could examine how many children pass all of the hypothesized easier versions of the task before a hypothesized more difficult task. That is, if the hypothesized ordering of component tasks from easiest to hardest is A, B, C, D, then the outcome of interest is how many children passed A, B, and C, but not D; A and B but not C and D; and A but not B, C, and D.

Carlson (2005) applied this method in a large sample aged 2–5 to determine the probability of passing common EF tasks at each age. Although the ordering of specific tasks varied from age to age, inhibition tasks routinely were passed earlier than WM tasks and the very hardest tasks consistently involved both inhibition and WM demands (e.g., reverse categorization at age 2, DCCS at age 3,

backward digit span at ages 3 and 4, advanced DCCS at ages 5–6).

Finally, longitudinal studies obviously are ideal to detect sequences, but few exist. Several longitudinal studies have examined the TOH or TOL task, with a focus on developmental sequences in strategy use (McNamara et al., 2007), and family, cognitive, school achievement, and social adjustment correlates (Friedman et al., 2007; Jacobson & Pianta, 2007). On inhibitory tasks, one striking sequence identified is that performance on a delay of gratification task at age 4 predicts, and thus may be a developmental precursor for, performance on inhibitory tasks such as the Go-No-Go task at age 18 (Eigsti et al., 2006). In a longitudinal study from ages 2 to 4 (Hughes & Ensor, 2007), EF (an aggregate of inhibition, WM, and shifting tasks) improved with age and showed stable individual differences, indicating the predictive ability of early EF for later EF.

This review suggests several influences on children's level of performance on EF assessments that should be considered when examining sequences. One complication in identifying sequences is that estimates of performance, and thus developmental trajectories, may vary, depending on what aspect of performance is scored and how it is scored (e.g., Baker et al., 2001; Huizinga et al., 2006). Moreover, the apparent developmental order of two aspects (A then B) of EF actually could be due to the greater performance demands of B. Reducing the demands of B would reverse the sequence. For this reason the design suggested above, with different versions of the same task, ideally would use similar levels of task difficulty. These measurement issues obviously become even more challenging when assessing the sequence of a task requiring one EF component and a task requiring two components.

Mechanisms identified. The studies reviewed here suggest several likely developmental mechanisms (biological and environmental) of EF development for the focus of future research. Consistent with most developmental EF theories, the assessment of brain activity is important because it provides clues about how developing EFs become organized, as seen in changes in neural networks and increased localization. Such research is well underway, although this research focuses on inhibition and WM, and rarely shifting. One influential developmental model (Posner & Rothbart, 2007) proposes that the development of the anterior attention system—the executive attention network—during preschool is important for regulating other brain networks.

Large neural and behavioral changes in the components during the preschool years are followed by more gradual, fine-grained improvements later. However, establishing *specific* links between brain changes and changes in behavior has proven to be more difficult. Also, distinguishing individual performance differences in brain activity from maturational differences continues to challenge neuroimaging researchers (Thomas & Tseng, 2008). One promising approach is to include several brain and behavioral measures and examine which ones change from one age to another and which do not. For example, LaVallee, Muenke, Robertson, and Watamura (2007) compared EEG responses, reaction time, number of gaze shifts, and accuracy on a modified Stroop task (e.g., see a boy, hear the word "girl") in 3- versus 4-year-olds. Another promising approach is one (Morton et al., 2009) in which age differences in neural correlates of component processes (shifting vs. processing of conflict) were examined separately.

Two points should be made about brain-based changes as possible mechanisms. First, any change in brain function could be either a cause (i.e., neural maturation provides a mechanism of development) or an effect (i.e., EF behaviors lead to brain changes) or both. Second, cognitive neuroscience work would contribute more to the existing behavioral literature if it were tied to theoretical developmental issues such as quantitative versus qualitative change, degree of generalization of new EF skills, and domain-specific versus domain-general EF skills.

As for experiential-based mechanisms of EF development, several studies reviewed (e.g., Crone, 2007; Crone et al., 2006; Davidson et al., 2006; Hogan et al., 2005; Somsen, 2007) suggest that metacognition may play an important role during the school-age years and adolescence. Examples are an awareness of inhibition failures and the subsequent adjustments in response to avoid future errors, as well as slowing one's response in order to ensure high accuracy on a switching task. Current developmental EF theories, because they are based mainly on development in the first 5 years of life, are limited in this respect. Post-preschool detection of success or failure of one's current rule (Zelazo), latent representation (Munakata), mental set or prepotent behavior (Diamond), or focus of attention (Posner & Rothbart) may be important metacognitive developments that would extend these theories based on preschoolers to older children. The relevant aspects of metacognition may vary

from one component to another. For example, it seems likely that knowing to slow down is particularly important in theories that emphasize inhibition, whereas detecting errors and considering alternative responses may be particularly important in theories emphasizing shifting.

Several other suspected contributors to EF include practice (e.g., McNamara et al., 2007), intense motor activity (Bell et al., 2007; Campbell, Eaton, & McKeen, 2002; Davis et al., 2007), language (Bell et al., 2007; for preschoolers only; Kray, Eber, & Lindenberger, 2004; Wolfe & Bell, 2004), bilingualism (Carlson & Meltzoff, 2008), maternal education and parenting (Friedman et al., 2007), and theory of mind (Hughes & Ensor, 2007; Perner & Lang, 2000)—understanding that mental states exist and affect behavior. Moreover, cultural differences, such as the earlier acquisition of EF in Chinese than U.S. children (e.g., Sabbagh et al., 2006), suggest that cultural values, perhaps as expressed in practices at school, may affect the development of EF.

Conclusions

Unlike previous reviews focused on preschoolers' EF, this review focused on EF across a much larger age span. This perspective permitted an examination of EF in light of central developmental issues such as the form of developmental trajectories, sequences of acquisition within EF development, qualitative and quantitative change, and developmental mechanisms at both behavioral and neural levels. Based on this framework of developmental issues, the key components of needed future research include: (a) use of a wide age range and comparable tasks to reveal the form of developmental trajectories of each EF component, (b) examination of several EF components so that relations among components can be examined, and (c) assessment of possible mechanisms of development. Such designs would move EF research from its current state—strong theoretical and empirical work on preschoolers, scattered nonintegrated work on older children, and emphasis on description of age differences—to a truly developmental account. This account would provide a developmental theoretical focus to cognitive neuroscience studies of children's EF. In turn, a more theoretically based developmental cognitive neuroscience would provide greater constraints on developmental issues and theories of EF than we have now.

References

- Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, 77, 1698–1716.
- Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, 8, 71–82.
- Asato, M. R., Sweeney, J. A., & Luna, B. (2006). Cognitive processes in the development of TOL performance. *Neuropsychologia*, 44, 2259–2269.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–90). New York: Academic Press.
- Baker, K., Segalowitz, S. J., & Ferlisi, M.-C. (2001). The effect of differing scoring methods for the Tower of London task on developmental patterns of performance. *The Clinical Neuropsychologist*, 15, 309–313.
- Barkley, R. A., Edwards, G., Laneri, M., Fletcher, K., & Metevia, L. (2001). Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). *Journal of Abnormal Child Psychology*, 29, 541–556.
- Bell, M. A., Wolfe, C. D., & Adkins, D. R. (2007). Frontal lobe development during infancy and childhood. In D. J. Coch, K. W. Fischer, & G. Dawson (Eds.), *Human behavior learning, and the developing brain: Typical development* (pp. 247–276). New York: Guilford.
- Berg, W. K., & Byrd, D. L. (2002). The Tower of London spatial problem solving task: Enhancing clinical and research implementation. *Journal of Experimental and Clinical Neuropsychology*, 25, 586–604.
- Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review*, 29, 180–200.
- Beveridge, M., Jarrold, C., & Pettit, E. (2002). An experimental approach to executive fingerprinting in young children. *Infant and Child Development*, 11, 107–123.
- Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology*, 26, 571–593.
- Campbell, D. W., Eaton, W. O., & McKeen, N. A. (2002). Motor activity level and behavioral control in young children. *International Journal of Behavioral Development*, 26, 289–296.
- Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology*, 28, 595–616.
- Carlson, S. M., & Meltzoff, A. (2008). Bilingual experience and executive functioning in young children. *Developmental Science*, 11, 282–298.
- Carlson, S. M., & Moses, L. J. (2001). Individual differences in inhibitory control and children's theory of mind. *Child Development*, 72, 1032–1053.
- Casey, B. J., Amso, D., & Davidson, M. C. (2006). Learning about learning and development with modern imaging technology. In Y. Munakata & M. H. Johnson (Eds.), *Processes of change in brain and cognitive development: Attention and performance XXI* (Vol. 21, pp. 513–533). Oxford, UK: Oxford University Press.
- Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., et al. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of Cognitive Neuroscience*, 9, 835–847.
- Cepeda, N. J., Kramer, A. F., & Gonzales de Sather, J. C. M. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology*, 37, 715–730.
- Conklin, H. M., Luciana, M., Hooper, C. J., & Yarger, R. S. (2007). Working memory performance in typically developing children and adolescents: Behavioral evidence of protracted frontal lobe development. *Developmental Neuropsychology*, 31, 103–128.
- Cragg, L., & Nation, K. (2008). Go or no-go? Developmental improvements in the efficiency of response inhibition in mid-childhood. *Developmental Science*, 11, 819–827.
- Crone, E. A. (2007, April). *Development of feedback processing and performance monitoring*. Paper presented at the meeting of the Society for Research in Child Development, Boston.
- Crone, E. A., Somsen, R. J. M., Zanolie, K., & Van der Molen, M. W. (2006). A heart rate analysis of developmental change in feedback processing and rule shifting from childhood to early adulthood. *Journal of Experimental Child Psychology*, 95, 99–116.
- Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, 44, 2037–2078.
- Davis, C. L., Tomporowski, P. D., Boyle, C. A., Waller, J. L., Miller, P. H., Naglieri, J., et al. (2007). Effects of aerobic exercise on overweight children's cognitive functioning: A randomized controlled trial. *Research Quarterly for Exercise & Sport*, 78, 510–519.
- Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E., et al. (in press). Exercise improves executive function and alters neural activation in overweight children: A randomized controlled trial. *Health Psychology*.
- DeMarie-Dreblow, D., & Miller, P. H. (1988). The development of children's strategies for selective attention: Evidence for a transition period. *Child Development*, 59, 1504–1513.
- D'Esposito, M., & Postle, B. R. (1999). The dependence of span and delayed-response performance on prefrontal cortex. *Neuropsychologia*, 37, 1303–1315.
- Diamond, A. (1990a). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. *Annals of the New York Academy of Sciences*, 608, 637–676.
- Diamond, A. (1990b). The development and neural bases of memory functions as indexed by the AB and

- delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences*, 608, 267–317.
- Diamond, A. (2006). The early development of executive functions. In E. Bialystock & F. I. M. Craik (Eds.), *The early development of executive functions. Lifespan cognition: Mechanisms of change* (pp. 70–95). Oxford, UK: Oxford University Press.
- Diamond, A., & Taylor, C. (1996). Development of an aspect of executive control: Development of the abilities to remember what I said and to “do as I say, not as I do.” *Developmental Psychobiology*, 29, 315–334.
- Durston, S., Davidson, M. C., Tottenham, N., Galvan, A., Spicer, J., Fossella, J. A., et al. (2006). A shift from diffuse to focal cortical activity with development. *Developmental Science*, 9, 1–20.
- Eigsti, I., Zayas, V., Mischel, W., Shoda, Y., Ayduk, O., Dadlani, M., et al. (2006). Predicting cognitive control from preschool to late adolescence and young adulthood. *Psychological Science*, 17, 478–484.
- Fischer, B., Biscaldi, M., & Gezeck, S. (1997). On the development of voluntary and reflexive components in human saccade generation. *Brain Research*, 754, 285–297.
- Flavell, J. H. (1972). An analysis of cognitive-developmental sequences. *Genetic Psychology Monographs*, 82, 279–350.
- Friedman, S. L., Vandergrift, N., Spieker, S., Hirsh-Pasek, K. A., Keating, D. P., Park, Y., et al. (2007, April). *First through fifth grade trajectories of Tower of Hanoi planning: family and cognitive predictors; math and reading correlates*. Poster presented at the meeting of the Society for Research in Child Development, Boston.
- Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin*, 134, 31–60.
- Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, 40, 177–190.
- Gerstadt, C. L., Hong, Y. J., & Diamond, A. (1994). The relationship between cognition and action: Performance of children 3½–7 years old on a Stroop-like day-night test. *Cognition*, 53, 129–153.
- Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences of the United States of America*, 101, 8174–8179.
- Goldman-Rakic, P. S. (1987). Development of cortical circuitry and cognitive function. *Child Development*, 58, 601–622.
- Hogan, A. M., Vargha-Khadem, F., Kirkham, F. J., & Baldeweg, T. (2005). Maturation of action monitoring from adolescence to adulthood: an ERP study. *Developmental Science*, 8, 525–534.
- Hughes, C. (1998). Executive function in preschoolers: Links with theory of mind and verbal ability. *British Journal of Developmental Psychology*, 16, 233–253.
- Hughes, C., & Ensor, R. (2007). Executive function and theory of mind: Predictive relations from ages 2 to 4. *Developmental Psychology*, 43, 1447–1459.
- Huizinga, M., Dolan, C. V., & Van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, 44, 2017–2036.
- Iacoboni, M., & Dapretto, M. (2006). The mirror neuron system and the consequences of its dysfunction. *Nature Reviews Neuroscience*, 7, 942–951.
- Isquith, P. K., Gioia, G. A., & Espy, K. A. (2004). Executive function in preschool children: Examination through everyday behavior. *Developmental Neuropsychology*, 26, 403–422.
- Jacobson, L. A., & Pianta, R. C. (2007, April). *Executive function skills and children’s academic and social adjustment to sixth grade*. Poster presented at the biennial meeting of the Society for Research in Child Development, Boston.
- Johnstone, S. J., Dimoska, A., Smith, J. L., Barry, R. J., Pleffer, C. B., Chiswick, D., et al. (2007). The development of stop-signal and go/nogo response inhibition in children aged 7–12 years: Performance and event-related potential indices. *International Journal of Psychophysiology*, 63, 25–38.
- Jonkman, L. M. (2006). The development of preparation, conflict monitoring and inhibition from early childhood to young adulthood: A go/nogo ERP study. *Brain Research*, 1097, 181–193.
- Jonkman, L. M., Lansbergen, M., & Stauder, J. E. A. (2003). Developmental differences in behavioral and event-related brain responses associated with response preparation and inhibition in a go/nogo task. *Psychophysiology*, 40, 752–761.
- Klenberg, L., Korkman, M., & Lahti-Nuuttila, P. (2001). Differential development of attention and executive functions in 3- to 12-year-old Finnish children. *Developmental Neuropsychology*, 20, 407–428.
- Klimkeit, E. I., Mattingley, J. B., Sheppard, D. M., Farrow, M., & Bradshaw, J. L. (2004). Examining the development of attention and executive functions in children with a novel paradigm. *Child Neuropsychology*, 10, 201–211.
- Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. *Journal of Cognitive Neuroscience*, 14, 1–10.
- Kray, J., Eber, E., & Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: The role of verbalization in task preparation. *Acta Psychologica*, 115, 143–165.
- Kwon, H., Reiss, A. L., & Menon, V. (2002). Neural basis of protracted developmental changes in visuo-spatial working memory. *Proceedings of the National Academy of Sciences USA*, 99, 13336–13341.
- Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and

- adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia*, 44, 2139–2148.
- LaVallee, S. E., Muenke, H. S., Robertson, S. S., & Watamura, S. E. (2007, March). *The development of executive control: Behavioral and neural activity in a proposed pediatric stroop task*. Poster presented at the meeting of the Society for Research in Child Development, Boston.
- Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, 21, 59–80.
- Lehto, J. E., & Uusitalo, A.-K. (2006). Rule detection in preschool-aged children. *European Journal of Developmental Psychology*, 3, 209–221.
- Leon-Carrion, J., García-Orza, J., & Pérez-Santamaría, F. J. (2004). Development of the inhibitory component of the executive functions in children and adolescents. *International Journal of Neuroscience*, 114, 1291–1311.
- Liston, C., Watts, R., Tottenham, N., Davidson, M. C., Niogi, S., Ulug, A. M., et al. (2006). Frontostriatal microstructure modulates efficient recruitment of cognitive control. *Cerebral Cortex*, 16, 553–560.
- Luciana, M., Conklin, H. M., Hooper, C. J., & Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Development*, 76, 697–712.
- Luciana, M., & Nelson, C. A. (1998). The functional emergence of prefrontally-guided working memory systems in four- to eight-year-old children. *Neuropsychologia*, 36, 273–293.
- McNamara, J. P. H., DeLuca, T. L., & Berg, W. K. (2007, March). *Children's executive functioning: A longitudinal and microgenetic study*. Poster presented at the meeting of the Society for Research in Child Development, Boston.
- Miyake, A. (2009, May). *Individual differences in executive function: Basic findings and implications for self-regulation research*. Paper presented at the meeting of the Association for Psychological Science, San Francisco.
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, 41, 49–100.
- Morton, J. B., Bosma, R., & Ansari, D. (2009). Age-related changes in brain activation associated with dimensional shifts of attention: an fMRI study. *NeuroImage*, 46, 336–358.
- Munakata, Y. (2001). Graded representations in behavioral dissociations. *Trends in Cognitive Sciences*, 5, 309–315.
- Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research*, 121, 391–400.
- Nagy, Z., Westerberg, H., & Klingberg, T. (2004). Maturation of white matter is associated with the development of cognitive functions during childhood. *Journal of Cognitive Neuroscience*, 16, 1227–1233.
- Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, 126, 220–246.
- O'Hare, E. D., & Sowell, E. R. (2008). Imaging developmental changes in gray and white matter in the human brain. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (2nd ed., pp. 23–38). Cambridge, MA: MIT Press.
- Olson, E. A., & Luciana, M. (2008). The development of prefrontal cortex functions in adolescence: Theoretical models and a possible dissociation of dorsal versus ventral subregions. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (2nd ed., pp. 575–590). Cambridge, MA: MIT Press.
- Perner, J., & Lang, B. (2000). Theory of mind and executive function: Is there a developmental relationship? In S. Baron-Cohen, H. Tager-Flusberg, & D. J. Cohen (Eds.), *Understanding other minds: Perspectives from developmental cognitive neuroscience* (2nd ed., pp. 150–181). New York: Oxford University Press.
- Polich, J. (1987). Task difficulty, probability and interstimulus interval as determinants of P300 from auditory stimuli. *Electroencephalography and Clinical Neurophysiology*, 63, 251–259.
- Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology*, 58, 1–23.
- Rennie, D. A. C., Bull, R., & Diamond, A. (2004). Executive functioning in preschoolers: Reducing the inhibitory demands of the Dimensional Change Card Sort task. *Developmental Neuropsychology*, 26, 423–443.
- Roberts, R. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, 12, 105–126.
- Romine, C. B., & Reynolds, C. R. (2005). A model of the development of frontal lobe function: Findings from a meta-analysis. *Applied Neuropsychology*, 12, 190–201.
- Rubia, K., Smith, A. B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., et al. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Human Brain Mapping*, 27, 973–993.
- Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 14931–14936.
- Sabbagh, M. A., Xu, F., Carlson, S. M., Moses, L. J., & Lee, K. (2006). The development of executive functioning and theory of mind: A comparison of Chinese and U.S. preschoolers. *Psychological Science*, 17, 74–81.
- Scherf, K. S., Sweeney, J. A., & Luna, B. (2006). Brain basis of developmental change in visuospatial working memory. *Journal of Cognitive Neuroscience*, 18, 1045–1058.
- Senn, T. E., Espy, K. A., & Kaufmann, P. M. (2004). Using path analysis to understand executive function

- organization in preschool children. *Developmental Neuropsychology*, 26, 445–464.
- Shimamura, A. P. (2000). The role of the prefrontal cortex in dynamic filtering. *Psychobiology*, 28, 207–218.
- Simpson, A., & Riggs, K. J. (2005). Inhibitory and working memory demands of the day-night task in children. *British Journal of Developmental Psychology*, 23, 471–486.
- Somsen, R. J. M. (2007). The development of attention regulation in the Wisconsin Card Sorting Task. *Developmental Science*, 10, 664–680.
- Steinberg, L. (2007). Risk taking in adolescence: New perspectives from brain and behavioral science. *Current Directions in Psychological Science*, 16, 55–59.
- Steinberg, L., Albert, D., Cauffman, E., Banich, M., Graham, S., & Woolard, J. (2008). Age differences in sensation seeking and impulsivity as indexed by behavior and self-report: Evidence for a dual systems model. *Developmental Psychology*, 44, 1764–1778.
- Stuss, D. T., & Benson, D. F. (1984). Neuropsychological studies of frontal lobes. *Psychological Bulletin*, 95, 3–28.
- Thomas, K. M., & Tseng, A. (2008). Functional MRI methods in developmental cognitive neuroscience. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (2nd ed., pp. 311–324). Cambridge, MA: MIT Press.
- Wellman, H. M., & Liu, D. (2004). Scaling of theory-of-mind tasks. *Child Development*, 75, 523–541.
- Welsh, M. C., Pennington, B. F., & Groisser, D. B. (1991). A normative-developmental study of executive function: A window on prefrontal function in children. *Developmental Neuropsychology*, 7, 131–149.
- Welsh, M. C., Satterlee-Cartmell, T., & Stine, M. (1999). Towers of Hanoi and London: Contribution of working memory and inhibition to performance. *Brain and Cognition*, 41, 231–242.
- Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, 35, 205–213.
- Wolfe, C. D., & Bell, M. A. (2004). Working memory and inhibitory control in early childhood: Contributions from physiology, temperament, and language. *Developmental Psychobiology*, 44, 68–83.
- Zelazo, P. D. (2006). The Dimensional Change Card Sort (DCCS): A method of assessing executive function in children. *Nature Protocols*, 1, 297–301.
- Zelazo, P. D., Muller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, 68(Serial No. 274).