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Executive functions after age 5: Changes and correlates

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ABSTRACT

Research and theorizing on executive function (EF) in childhood has been disproportionately focused on preschool age children. This review paper outlines the importance of examining EF throughout childhood, and even across the lifespan. First, examining EF in older children can address the question of whether EF is a unitary construct. The relations among the EF components, particularly as they are recruited for complex tasks, appear to change over the course of development. Second, much of the development of EF, especially working memory, shifting, and planning, occurs after age 5. Third, important applications of EF research concern the role of school-age children's EF in various aspects of school performance, as well as social functioning and emotional control. Future research needs to examine a more complete developmental span, from early childhood through late adulthood, in order to address developmental issues adequately.

For several decades research has reported deficits in the regulation of cognition, emotion, and behavior—but intact sensory processing, movement, speech, and even intelligence—in adult patients with frontal lobe damage (e.g., Stuss & Benson, 1984). As a result of these early neuropsychological studies, researchers (e.g., Luria, 1966) postulated that the prefrontal cortex (PFC) was critical to the planning, organization, and regulation of cognition and behavior. Over the years, primate (e.g., Goldman-Rakic, 1995), lesion (e.g., Stuss et al., 2000), and neuroimaging studies (Konishi et al., 1998) have supported this functional description of the PFC, and recently researchers have attempted to form a concise characterization of those functions.

Executive function (EF) serves as an umbrella term to encompass the goal-oriented control functions of the PFC. Relatively complex neuropsychological instruments such as the Wisconsin Card Sort-

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ing Test (WCST) were first employed to evaluate frontal lobe functioning and later to assess EF (Eling, Derckx, & Maes, 2008). By assessing participants' ability to plan ahead, to reflect on their performance, and to alter that performance if necessary, the WCST is more sensitive to *how* participants complete the task than to *what* factual knowledge can be retrieved to complete the task. However, the WCSTs complexity also makes it difficult to specify exactly what those *how* processes are, and it likely requires a variety of executive processes—a problem of task impurity (Hughes & Graham, 2002; Miyake et al., 2000). Thus, it is difficult to ascertain what specific cognitive deficit underlies poor performance. This problem, along with evidence for modularity of functions within the PFC (e.g., Moscovitch & Winocur, 2002), have spurred the creation and implementation of simpler, more precise assessments to complement or replace the classic neuropsychological tasks.

At the same time, the call for a better understanding of children's development of EF (Hughes, 1998; Hughes & Graham, 2002) has made it necessary to develop simplified EF tasks. Initially, much of the interest focused on the study of atypical development, notably ADHD and autism (Hughes & Graham, 2002). Recently, as attention has shifted toward normal EF development, a disproportionate amount of this research has investigated the age during the preschool years at which specific components of EF emerge, to the neglect of their later developmental course towards complete maturation.

There are good reasons to focus on preschoolers. First, such work identifies the very beginnings of each component of EF. Researchers have modified EF tasks used with adults to make them suitable for young children, who have limited ability to understand and follow instructions, as well as handle complex tasks (see Garon, Bryson, & Smith, 2008, for a review). Moreover, some of these simplified tasks may assess a single EF component, thus avoiding the problem of task impurity, specifically, that the complex tasks used with adults place demands on multiple EF components or on both executive and non-executive processes (Hughes & Graham, 2002; Miyake et al., 2000). Finally, the focus on preschoolers has revealed important relations between EF and theory of mind (e.g., Hughes & Ensor, 2007).

While these are important issues about EF development that require its examination in young children, there are also good reasons to assess EF development in school-age children. Such research allows us to ask questions that cannot be answered in research with preschoolers. First, examining a broader age range may clarify certain issues about EF as a construct, specifically, whether we should view EF as a unitary process or as a set of multiple, distinct component processes. The relations among components may change developmentally, making it critical to include older children. Similarly, children of different ages may coordinate the components in different ways and find different aspects of EF challenging when carrying out goal-oriented behavior. For example, inhibition may be particularly difficult for young children. Research on both of these issues—further changes in the development of each EF component and in the relations among the components during later childhood and adolescence—would not only clarify EF as a construct but also provide insight into processes underlying the development of EF.

Second, significant improvements in EF tasks occur during the school years (Romine & Reynolds, 2005). By excluding school-age children, we miss much of the developmental picture of EF, specifically, the distinct developmental trajectories of each EF component (e.g., working memory, inhibition, shifting) during middle childhood and adolescence. Moreover, there may be sleeper effects, in which experiences or individual differences in early childhood do not show observable effects until middle childhood. This event or change may be very small in early childhood, but eventually lead to large change much later on. For example, small effects of EF on theory of mind during the preschool years might lead to larger effects on social interaction during middle childhood.

To complete this developmental picture, it is necessary to consider the impairments to EF as part of the normal aging process. EF seems to be particularly vulnerable to cognitive aging, and its decline certainly impacts social functioning (von Hippel, 2007). As with studying the developmental trajectories of EF components in childhood and adolescence, the course of typical EF decline should clarify the interaction of EF components to produce goal-oriented behavior and the nature of brain processes supporting EF.

A third reason to study children older than preschool age is that entry into middle childhood means entry into a new set of experiences, and thus new questions can be asked about the uses of EF in everyday life. In particular, we can examine the relations to various aspects of schooling (e.g., academic achievement, time-management skills, and school-related behavior). For example, because EF deficits are prominent in ADHD (e.g., Weyandt, 2005), a disorder marked by poor school functioning, it is likely that proper EF is critical to school achievement. Another change in contexts of development is that the peer group becomes increasingly important, raising questions about the relations between EF and social functioning. Thus, a wider range of outcomes can be studied in older children.

For these reasons, unlike other review papers on EF, which focus on the preschool years (e.g., Garon et al., 2008), the purpose of this paper is to examine the development of EF during grade school and adolescence as it reaches maturation and to examine its decline as a part of the normal aging process. The review is organized around the above three topics—EF as a construct, the developmental trajectories of the various components of EF in middle childhood and adolescence but also during aging, and the function of EF in daily life.

One advantage of studying EF in school-age children is that many of the methodological issues that arise in the study of EF in young children, such as limited understanding of instructions and fatigue (e.g., Luciana, 2003; Luciana & Nelson, 2002), are less pronounced in older children. To address young children's limitations, researchers often must simplify tasks or use shorter and more interesting tasks than those used with older children (e.g., Dibbets & Jolles, 2006). The problem with this approach is that one cannot be certain whether these simplified tasks assess the same underlying EF components as the original ones. According to Luciana (1997), only when an EF process first emerges is it appropriate to use simplified tasks. If, however, the researcher wants to make comparisons to adults (e.g., to determine when adult levels of proficiency are reached), then the same tasks used in adult assessment need to be used with the child sample. Such problems of achieving comparability are much less serious in school-age and adolescent samples. Moreover, school-age samples are more likely to have equivalent variance across age groups and thus meet homogeneity of variance assumptions, and to produce a sufficient degree of individual variation for a given age group (Archibald & Kerns, 1999).

A final methodological advantage of studying EF in school-age children is that brain neuroimaging assessments, critical for showing related changes in brain structure, function, and connectivity between brain regions, can more easily be added. With preschoolers, it is difficult to obtain decent image quality, which requires that the participant remain still in the MRI scanner. Such young children often must be scanned under sedation, thus prohibiting functional imaging (Wood & Smith, 2008). As noted above, the term *executive function* arose to describe a set of functions ascribed to the functioning of the PFC—the cortex of the frontal lobe that is anterior to the supplementary motor area. It comprises one-quarter to one-third of the cerebral cortex and contains rich reciprocal connections within itself, with other cortical areas, and with subcortical and limbic brain regions (Olson & Luciana, 2008). Employing a neural network conceptualization of brain functioning, researchers have suggested that the PFC subserves EF by activating and inhibiting posterior cortical and subcortical brain structures (Aron, 2008; Braver & Barch, 2002; Casey, Amso, & Davidson, 2006; Shimamura, 2000). PFC activity also maintains pertinent information in working memory (WM) (e.g., "respond when I see X but not when I see Y") and prohibits irrelevant information from entering WM (Olson & Luciana, 2008; Shimamura, 2000).

Like brain development in general, PFC development involves both progressive (e.g., neuron proliferation, synaptogenesis, and myelination) and regressive (e.g., cell death, synaptic pruning) changes (Casey et al., 2006; O'Hare and Sowell, 2008). Through much of development, progressive and regressive changes (e.g., myelination and synaptic pruning, respectively) occur concurrently, driven in part by the child's experiences, to create an efficient neural network supporting EF (O'Hare and Sowell, 2008). However, there are regional variations in the timing of these changes. The PFC follows a particularly protracted timetable to maturation, unlike other brain regions that mature earlier in childhood (e.g., regions responsible for motor and sensory processing, speech and language development, and attention) (Gogtay et al., 2004; O'Hare and Sowell, 2008). Thus, the general finding that EF develops throughout adolescence, discussed in more detail below, is affirmed by the protracted development of the PFC. Regarding the opposite end of the lifespan, knowledge that the PFC is vulnerable to several forms of deterioration has been important in characterizing age-related cognitive decline (Burke & Barnes, 2006).

Two prominent techniques in developmental neuroscience that examine the relationship between neural development (e.g., PFC) and behavioral development (e.g., EF) are (1) to determine correlations between structural brain changes and changes in task performance and (2) to measure functional activity underlying task performance and determine how that activity changes across development. Both techniques have been utilized to examine how the neural correlates of EF change over time to produce mature EF.

EF as a construct

One issue that can be explored fully only by including older children and adolescents as well as preschoolers concerns the nature of the EF construct. Two key questions arise: First, is EF best thought of as a unitary process or as a set of multiple, distinct component processes? And second, if EF does refer to distinct component processes, how are these processes related and how does this relationship change as the child develops?

Concerning the first question, most studies of preschool and school-age children (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Asato, Sweeney, & Luna, 2006; Bull & Scerif, 2001; Hughes, 1998; Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; St. Clair-Thompson & Gathercole, 2006) support the view that EF consists of related but separable components (i.e., the unity-but-diversity view) and purport that a common mechanism (or mechanisms) underlies all EF processes (Miyake et al., 2000). (See, however, Bernstein & Waber, 2007 who caution against the modularity conceptualization of EF, and Wiebe, Espy, & Charak, 2008, who found evidence for unitary EF in children aged 2–6). In some of these studies, path and factor analyses over childhood and adolescence demonstrate that performance on tasks of one particular domain (e.g., inhibition) is highly correlated and loads onto one distinct latent variable while performance between separate domains (e.g., between inhibition and working memory) is also correlated, but more modestly. Consequently, these domains represent distinct latent variables.

Other evidence also supports the unity-but-diversity view: (1) The different developmental trajectories over childhood and adolescence detailed below undermine the notion of a completely unified EF. That is, ages of maturity of the components and the periods of most rapid change come at somewhat different ages for different components. (2) Neuroimaging research indicates that multiple EF tasks that span different EF domains recruit slightly different regions of the PFC, including mid-dorsolateral and mid-ventrolateral prefrontal regions (Olson & Luciana, 2008), as well as the anterior cingulate cortex (Bell & Wolfe, 2004; Bernstein & Waber, 2007; Rubia et al., 2006). The commonality is that, though the specific regions are distinct, activation occurs in the fronto-striatal region, suggesting a unity but diversity of activated brain regions. (3) Support for the unity-but-diversity view has been found at multiple developmental time points, including the preschool years (Hughes, 1998; Senn, Espy, & Kaufmann, 2004), preadolescence (Huizinga et al., 2006; Lehto et al., 2003), young adulthood (Miyake et al., 2000), and to some extent middle and late adulthood (Fisk & Sharp, 2004; Zelazo, Craik, & Booth, 2004). (4) A particular deficit, such as poor academic performance in a specific area (see below) is associated with a greater impairment for some EF components than others, which suggests some independence.

Nevertheless, one lingering question is what those components are. For example, the articles examined for this review suggested more than 15 components. Many researchers now are following Miyake et al's (2000) focus on three "foundational" components: shifting, inhibition, and updating of WM (e.g., Huizinga et al., 2006; Lehto et al., 2003). An advantage of examining these particular EF components is that there are a number of frequently used, relatively simple cognitive tasks that ostensibly tap into each dimension (Miyake et al., 2000). In addition to the foundational EFs, planning is often cited in the literature as critical to goal-oriented behavior. As Anderson (2002) describes, planning is an essential part of goal-setting, for it involves the ability to plan actions in advance and to approach a task in an organized, strategic, and efficient manner.

In contrast, others have argued that working memory (WM) and inhibition are practically inseparable constructs that comprise the core of EF (e.g., Bell, Wolfe, & Adkins, 2007; Braver & Barch, 2002; Davidson, Amso, Anderson, & Diamond, 2006; Roberts & Pennington, 1996). Roberts and Pennington (1996) proposed an interactive framework of WM and inhibition: When one goal-oriented action is activated in WM, then by default other actions are inhibited from entering WM. Because they are interactive, increasing WM demands also compromises inhibitory abilities, leading to increased perseverative or commission errors. In addition, Braver and Barch (2002) offered a computation model in which a single gating mechanism subserves both WM and inhibition by allowing certain information to enter WM but prohibiting other information from entering. Currently, both behavioral (Beveridge, Jarrold, & Pettit, 2002; Simpson & Riggs, 2005) and functional neuroimaging (Aron, 2008) research suggest the independence of inhibition and WM; however, a remaining methodological challenge is to create EF tasks that isolate and assess one or the other EF component.

Another area of contention concerns the second question—how the specific components of EF are related developmentally. That is, at each age how do the components interact to produce goal-oriented behavior? One technique to examine this issue is structural equation modeling (SEM), which can clarify the relation among several variables and examine the indirect as well as direct effects of certain variables on task performance. In other words, SEM allows the researcher to examine what (and how) EF domains are recruited during complex problem solving.

Senn et al. (2004) showed that relations among EF components change developmentally. They assessed inhibition, WM, shifting, and TOL performance in children aged 2 years, 8 months to 6 years, 0 months. When ages were combined, in the best-fitting model, WM and inhibition were moderately correlated ($r = .27$) and both predicted TOH performance ($r = .40$ and .26, respectively). Importantly, shifting was unrelated to WM, inhibition, and TOH performance. However, when they split the sample into two age groups (i.e., younger versus older than 4 years), they found different patterns of relations. Thus, it is important to look at different age groups separately when examining the relations among EF components. For the younger children, only inhibition predicted TOH performance although the WM and inhibition factors remained moderately correlated. Conversely, for the older children, only WM predicted TOH performance, and the relationship between WM and inhibition dropped below significance. The authors surmised that these findings represent the differential course of development for EF components. Inhibition, which purportedly develops first, is heavily relied upon by younger children during problem solving. For older children, who apparently have also developed significant WM, this latter capacity becomes particularly important during problem solving. Importantly, the findings suggest that the skills that can be drawn on to solve complex problems change over development; which is to say, the relations among EF components change with age.

Huizinga and van der Molen (2007) found a similar developmental change in focus from inhibition to WM at older ages. They dissected successful WCST task performance into two distinct abilities: 1) switching to the new sorting rule on the basis of feedback and 2) maintaining the current sorting rule when appropriate. Only for 7-year-olds did these two abilities emerge as distinct factors. The ability to switch to the new sorting rule—Factor 1—was predicted by performance on simple shifting tasks, whereas the ability to maintain the current sorting rule—Factor 2—was predicted by performance on simple inhibition tasks. For the older three groups, only one factor emerged from the analysis, but the make-up of that factor differed across those three age groups. In 11-year-olds, the single factor was best predicted by shifting performance; in 15-year-olds, the single factor was best predicted by shifting and WM performance; and finally in 21-year-olds, the factor was best predicted by WM performance alone. Consistent with Senn et al. (2004), younger children appear to rely on inhibition more so than older children, perhaps because it develops earlier than other abilities.

Also consistent with this, Isquith, Gioia, and Espy (2004) found that EF is less differentiated in younger children than in older children. Inhibition appears to play a particularly important role for younger children, who may be more susceptible to distractions in the environment, which demands that inhibition emerge first in order to ignore irrelevant stimuli before problem solving can develop further. Or, children's ability to inhibit their prepotent response, and "stop and think," may be an essential first step. As children become adept at inhibiting responses to irrelevant environmental distractions and their own initial responses, other EFs—namely WM and shifting—can differentiate to negotiate complex problems in their environment. Once children have developed a certain level of inhibition they may be able to benefit from increased WM and focus on an emerging ability to shift, and, eventually, on planning skills. It may be that as a particular EF comes "online," the child allocates more effort to that EF during goal-oriented behavior than other EFs that emerged at an earlier time point, and thus these newer skills become better honed. The previously developed EF may even scaffold the newly emerging EF, as when inhibiting a prepotent response may permit the child to think about other possible responses on shifting tasks. Alternatively, a bias toward novelty and variability may facilitate the emergence of a new EF skill. In these ways children actively participate in their own development. High priority for future research is a focus on these processes during development.

Knowledge of what EF skills are recruited during successful completion of complex problem solving is important not only for theoretical reasons, but also for practical ones, such as developing interventions for school children with poor EF. The intervention can be tailored to the child's developmental level and cognitive abilities, and thus bolster the specific EF processes required (Naglieri & Gottling, 1997).

In conclusion, SEM of complex problem solving tasks is promising for addressing the degree of unity of EFs, for examining the specific subcomponents (i.e., the foundational EFs) recruited during problem solving at various ages, and for identifying the relations among the EFs at various developmental levels. Only by including older children and adolescents, as well as preschoolers, can these questions be addressed satisfactorily.

The developmental trajectories of EFs

Given the support described above for Miyake's unity-but-diversity framework, this overview of developmental trajectories will focus on the foundational EFs (shifting, inhibition, and updating) as well as on planning in school age-children and adolescents. Both behavioral and neural changes will be discussed. (For a more exhaustive account of the developmental trajectories for these four components, as well as a consideration of developmental issues involved, see Best & Miller, submitted for publication).

Inhibition

Although most researchers agree that inhibition is fundamental to EF, inhibition appears not to be a uniform process. Inhibition commonly refers to the ability to suppress a dominant, automatic or prepotent response, but inhibition also entails interference control, directed forgetting, emotional control, and motor control (Nigg, 2000). In addition, inhibitory demands seem to vary depending on whether WM is also needed (Garon et al., 2008; Roberts & Pennington, 1996), on the response modality (e.g., motor, oculomotor, or verbal response; Diamond & Taylor, 1996; Nigg, 2000), and on the degree of response prepotency (Diamond & Taylor, 1996). Research on the development of inhibition, however, typically has neither specified adequately the form of inhibition assessed nor attempted to relate its various forms (but see Nigg, 2000 for a comprehensive taxonomy of inhibitory processes).

Research documents rapid improvements in early childhood on tasks such as the Day/Night task, Luria's fist and finger game, and the A-not-B task (e.g., Carlson & Moses, 2001; Hughes, 1998; Sabbagh, Xu, Carlson, Moses, & Lee, 2006). These tasks involve, respectively, saying "day" when seeing a moon and "night" when seeing the sun, making a fist when the experimenter points a finger and vice versa, and reaching for an object in its current hiding place rather than its original hiding place. In the preschool years children significantly reduce their inhibition errors (e.g., saying 'Day' rather than 'Night' when shown a picture of the sun).

Although improved inhibition during the preschool years is striking, significant improvements also occur later, particularly between ages 5 and 8 (Romine & Reynolds, 2005). Several studies have found continued improvements in middle childhood on (a) motor inhibition tasks, such as Luria's hand game (Klenberg, Korkman, & Lahti-Nuuttila, 2001), (b) oculomotor inhibition tasks, such as an antisaccade task that requires looking in the opposite direction of an arrow (Luna, Garver, Urban, Lazar, & Sweeney, 2004) and a flanker task that requires looking in the direction of the middle stimulus such as a fish facing left and ignoring surrounding fish facing right (e.g., Simonds, Kieras, Rueda, & Rothbart, 2007; but see Rueda et al., 2004, for no change after age 8), and (c) simple response inhibition tasks, such as the Go/No-go task (Brocki & Bohlin, 2004; Davidson et al., 2006; Huizinga et al., 2006; Lehto et al., 2003; Simpson & Riggs, 2005). There appears to be little further improvement during adolescence and adulthood (Romine & Reynolds, 2005). However, Huizinga et al. (2006) found continued improvement in inhibition 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, indicating the gradual maturation of cognitive inhibition through adolescence and even early adulthood (e.g., Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004). Complex cognitive inhibition tasks appear to be more sensitive to the subtle improvements in performance than simpler conflict tasks (e.g., the Day/Night task) or motor inhibition tasks (e.g., the Statue task which requires the child to stay still, posing as a statue). Unlike the fundamental changes during preschool (e.g., acquisition of the ability to inhibit a prepotent response consistently), changes during adolescence mainly consist of refinements in speed and accuracy.

Computerized inhibition tasks are particularly useful for detecting improvements in inhibition during late childhood and adolescence because they present numerous trials and are able to measure behavioral variables (e.g., reaction time) very precisely. For example, Klimkeit, Mattingley, Sheppard, Farrow, and Bradshaw (2004) created a novel task similar to the Go/No-go task and Continuous Performance Task in that the child was required to respond to certain stimuli presented on the computer screen while inhibiting response to distractor stimuli. They found that 8-year-olds made more errors of inattention, impulsivity, and distractibility—suggestive of immature inhibition—than did 10- and 12-year olds.

Behavioral improvements in inhibition appear to be paralleled by refinements in the underlying brain activity in the PFC and in networks that include the PFC. Both neuroimaging (e.g., Casey et al., 1997; Durston et al., 2002, 2006; Liston et al., 2006) and EEG techniques (e.g., Bell & Wolfe, 2007; Lamm, Zelazo, & Lewis, 2006) document this change. Durston and colleagues (Durston et al., 2002, 2006) suggested that brain activation (measured via fMRI) during inhibition tasks (e.g., the Go/No-go task) transitions from being diffuse to being focalized during development. In particular, school-age children show diffuse activation of regions in the frontal cortex (e.g., bilateral ventral and dorsolateral regions) and in the parietal cortex as compared to adults. Only activation in the ventral frontal area (which positively correlated with task performance) increased after childhood.

Similarly, Lamm et al. (2006), using EEG measures, found decreases in frontal N2 amplitude—a negative wave produced after successful inhibition—from ages 7 to 17 on no-go trials of a Go/No-go task. The authors suggest that this decrease in frontal N2 amplitude indicates increasing neural efficiency and may be caused by "regressive developmental processes (e.g., synaptic pruning) in regions of PFC" (p. 2146). In support of the idea that frontal N2 activity corresponds to an inhibition mechanism, performance on the Stroop task and Iowa Gambling Task—both considered to tap into inhibition—predicted frontal N2 amplitudes beyond that predicted by age. Further, it appears that there is a migration in the source of electrical activity related to both age and performance on the inhibition tasks. Migration appears in two forms: First, there is evidence for the frontalization of cingulate activity with increased inhibition ability; second, orbitofrontal activity shifts from left-lateralized to right-lateralized with increasing age and performance. Perhaps the fine-grain improvements through late childhood and adolescence in inhibition are a reflection of the focalization and migration of activity in frontal brain regions.

Finally, a third technique, Diffusion Tensor Imaging (DTI), assesses the connectivity of various brain regions by measuring the diffusion of water in different regions of the brain (e.g., Nagy, Westerberg, & Klingberg, 2004), which in turn can be related to the development of behavior (Amso & Casey, 2006). In a study (Liston et al., 2006) using the Go/No-go task as a measure of inhibition and DTI as a measure of brain connectivity, both frontostriatal connectivity and connectivity in a comparison region (corticospinal) correlated with age. Only frontostriatal connectivity, however, correlated with Go/No-go task performance, suggesting that part of inhibition development during adolescence involves increasing connectivity between frontal cortex and the striatum. Taken together, these three measures of brain activity (fMRI, EEG, DTI) suggest that in addition to the focalization and migration of activity, perhaps increasing connectivity of frontal brain regions serves to enhance inhibition in later childhood.

Working memory (WM)

Generally speaking, WM involves the ability to maintain and manipulate information over brief periods of time (Alloway, Gathercole, & Pickering, 2006; Huizinga et al., 2006). Gathercole, Pickering, Ambridge, and Wearing (2004) found a linear increase in performance from age 4 to 15 for a battery of

WM tasks of varying complexity (except for a visual patterns task, which leveled off around age 11). As with inhibition tasks, there is evidence that task complexity affects performance on WM tasks (Luciana, Conklin, Hooper, & Yarger, 2005). Luciana et al. (2005) examined non-verbal WM tasks of varying complexity, ranging from a nonverbal face task (least complex) to a spatial self-ordered search (most complex). The former required the maintenance of a facial image in WM over a brief delay while the latter required the child to search varying locations on a computer screen for hidden tokens, remember searched areas, and strategically explore new locations. As predicted, the age-related changes in performance depended on the complexity of the particular task. From age 9 to 20, there were no performance differences on the simple face recognition task; there were steady improvements, however, on the most difficult self-ordered search until age 16. Thus, it is important to consider the complexity of the task when extrapolating a general trajectory of WM development

In both these studies, the use of qualitatively different tasks to manipulate task complexity potentially introduces confounds (e.g., differences in EF and non-EF recruitment between tasks) that influence age-related variation in performance not directly related to WM demands. To eliminate such confounding, Luciana and Nelson (1998) utilized a self-ordered search that varied in complexity only in a quantitative manner (i.e., the number of locations the child may search for tokens ranging from 2 to 8). For the least demanding condition, performance was equivalent among children ages 4–8, adolescents (M_{age} = 16.87), and adults (M_{age} = 23.06). Age-related performance differences did emerge as the number of search locations increased: For three search locations, performance leveled off at age 6, for 4 search locations, performance leveled off around age 17, and for 6 and 8 search locations, performance differences were observed among all groups. This study suggests that even young, preschool age children can hold a couple of items in mind simultaneously and that only by increasing the memory load do developmental differences emerge. Thus, WM development apparently continues through adolescence, and easier WM tasks are mastered before more complex ones.

Neuroimaging studies also point to continued changes in brain activity associated with WM through childhood and adolescence (e.g., Klingberg, Forssberg, & Westerberg, 2002; Nagy et al., 2004; Scherf, Sweeney, & Luna, 2006). For example, Scherf et al. (2006) found both qualitative changes (location of activation) and quantitative changes (amount of activation) from childhood (M_{age} = 11.2) through adulthood (M_{age} = 29.5) on a visual memory-guided saccade task. The children recruited qualitatively different premotor regions, including the lateral cerebellum, compared to adolescents and adults. Moreover, children relied more heavily on ventromedial regions, including the thalamus and basal ganglia. Thus, from childhood to adolescence there was a qualitative change in premotor activation and also a quantitative decrease in ventromedial activity. During adolescence (M_{age} = 15.7) activity shifted more to frontal regions, including a sharp increase in right dorsolateral PFC activation and the first significant activation of the anterior cingulate. Adults showed additional qualitative and quantitative change, including focalization in the left dorsolateral PFC as well as a fourfold increase in anterior cingulate activity. Conversely, activity within the right dorsolateral PFC decreased between these two age groups. Overall, these changes lead to a visuospatial WM network specialized to maintain visuospatial information. These results suggest further refinement of WM through adolescence as the prefrontal regions become more specialized for WM. Paralleling the behavioral findings on inhibition, these results suggest that the large improvements in WM in early childhood, along with qualitative changes in brain recruitment, are followed by more subtle refinements consisting of quantitative changes in activation and focalization of brain regions related to WM.

Shifting

The final foundational EF regards the ability to shift between mental states, operations, or tasks and is often referred to as "task switching" or "shifting" (Miyake et al., 2000). In the classic shifting task, the WCST, the participant is asked to sort cards based on a specific dimension (e.g., shape) to which she receives positive or negative feedback. At a set point, undisclosed to the participant, the sorting rule changes as indicated by negative feedback; it is at this point that the participant must determine the new sorting rule (e.g., color) and sort accordingly. Successful task switching involves inhibition of previously activated mental sets while failures of shifting appear in the form of perseverative errors (i.e., continuing to respond according to the previous set of rules) after a change in the response set (Anderson, 2002).

The ability to shift between more complex task sets, each with more numerous and complex rules improves with age, typically until early adolescence (e.g., Anderson, 2002; Cepeda, Kramer, & Gonzales de Sather, 2001; Crone, Somsen, Zanolie, & Molen, 2006; Huizinga & van der Molen, 2007; Huizinga et al., 2006; Somsen, 2007). Although 3- and 4-year-olds can reliably shift between two simple, contextualized response sets in which the rules are clearly discernable (Hughes, 1998), on a more complex shifting task (shifting between responding to either lines or shapes on a computer screen) further improvement occurs between ages 5 and 6 (Luciana & Nelson, 1998). This change was not in shifting *per se*, but in the ability to apply the set rules to new examples of lines and shapes—that is, to generalize the rules to new, unseen objects. Moreover, with increasing age, there was a steady increase in the proportion of children who successfully completed all stages of the task.

Shifting ability also may be measured in terms of shift cost, which is the difference either in response time or accuracy between shift trials and non-shift trials. Huizinga et al. (2006) found that the shift cost (measured in terms of response time) was significantly greater for 7- and 11-year-olds than for 15-year-olds, who showed shift cost equivalent to the young adult group (M_{age} = 20.8). Davidson et al. (2006) calculated a separate switch cost for accuracy and response time (RT). While the switch cost in accuracy declined between 9- and 13-year-olds, the RT switch cost actually increased between 6-year-of-age and adulthood. The authors reason that a speed-accuracy tradeoff is in effect, with older children as well as adults compromising their response times in order to ensure high accuracy. This increasing awareness of the relationship between speed and accuracy in childhood suggests the emerging presence of metacognition and its contributions to developmental differences in task performance.

Assessments of brain activity show higher EEG power values in the right frontal scalp regions by age 8 (Bell et al., 2007). In another study (Rubia et al., 2006), children aged 10–17 years were compared to adults aged 20–43. Both a group comparison (i.e., children compared to adults) and age correlation analyses indicated that, with age, activation increased in inferior frontal, parietal, and anterior cingulate regions. These findings support previous work that suggests that mature task shifting is related to inferior frontal and parietal regions as well as superior temporal regions in adults (Smith, Taylor, Brammer, & Rubia, 2004).

Planning

Perhaps the pinnacle of executive functioning is the ability to plan. Planning is a critical part of goal-oriented behavior; it embodies the ability to formulate actions in advance and to approach a task in an organized, strategic and efficient manner (Anderson, 2002). Planning both directs and evaluates behavior when children face a novel situation (Das, Naglieri, & Kirby, 1994). Tasks that evaluate planning ability require the child to prepare multiple steps of action in advance, to evaluate those actions, and to change course if necessary. The most frequently used tasks are the Tower of Hanoi (TOH) and the Tower of London (TOL), both of which present the participant with a number of colored disks or balls that need to be moved between three pegs in order to reproduce a target pattern in a set number of moves (Baker, Segalowitz, & Ferlisi, 2001). The participant must keep the target pattern in mind in order to create a strategy (e.g., the particular sequence of moves) and in order to evaluate his or her progress after each move. Task difficulty is manipulated by increasing the number of moves required to reach the solution (i.e., the final target pattern of disks or balls), which typically ranges from 2 to 5 moves, or by increasing the number of balls in the task (usually between 3 and 4 balls).

As with tasks of WM, the particular age at which mastery is reached depends on the difficulty of the TOL or TOH task condition (Baker et al., 2001; Huizinga et al., 2006; Lehto et al., 2003; Luciana & Nelson, 1998; Welsh, Pennington, & Groisser, 1991). Luciana and Nelson (1998) found that for the two-move TOL condition there were no significant performance differences among 4- to 8-year-olds or between 8-year-olds and adults. For the three-move condition, only 4-year-olds performed more poorly than adults. In contrast, for both the 4- and 5-move conditions, all children ages 4–8 performed similarly, which was significantly worse than adults. Altogether, the ability to effectively plan up to three moves is present by middle childhood, but the ability to effectively create more complex plans of 4 or 5 moves seems to develop at some point in late childhood or adolescence.

Huizinga et al. (2006) found different points of mastery for different measures of performance during late childhood and adolescence. For example, adult levels of performance measured in terms of both the number of extra moves required to achieve the target solution and the amount of planning time required prior to making the first move was reached by age 15. In contrast, performance steadily increased through adolescence when performance was measured in terms of the proportion of perfect solutions (i.e., completing the task condition in the absolute minimum number of moves) obtained out of the entire task set. Because large gaps separated the age groups (i.e., each age group was separated by four years), it is hard to extract the exact form of the developmental trajectory. Importantly, it also appears that the manner in which performance was measured affected the exact developmental trajectory observed (see also Baker et al., 2001).

Overall, planning ability seems to follow a protracted developmental course such that performance improves at least into late childhood and often adolescence (see also Anderson, Anderson et al., 2001; Asato et al., 2006 for further support for the protracted development of planning ability). Little is known about the brain changes related to the development of planning skills. Luciana, Schissel, Collins, and Lim (2007) found improvement during adolescence in TOL performance associated with increases in the organization of white matter in regions known to be activated by the task. More research on neural correlates of planning behavior would enrich our current understanding of its development.

Aging and executive function

Despite showing a protracted development and late age of maturation, EF seems to be particularly vulnerable to age-related cognitive declines (Dempster, 1992; Jurado & Rosselli, 2007). Beginning in the 7th decade of life impairments are evident on a wide variety of tasks—such as attentional control, response inhibition, planning, set shifting, and verbal fluency—that share the common thread of requiring executive abilities (Jurado & Rosselli, 2007). The WCST, in particular, commonly has been used to assess EF in older adults. In a meta-analysis of studies comparing older adults' WCST performance to younger adults, Rhodes (2004) concluded that two WCST performance measures (number of categories achieved and number of perseverative errors) indeed were sensitive to age-related cognitive decrements ($ES = -1.29$ to -1.13). Although education did act to buffer performance declines, the effects of age were stronger: Adults aged 75 or older performed close to 2 standard deviations below the mean of younger adults ($M = 25$ years of age). Memory functioning also appears to be impacted by the aging process, particular the maintenance and manipulation of information (i.e., WM) and the conscious recollection of specific events (i.e., episodic memory) (Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006). Both forms of memory are considered to require executive processes (e.g., Moscovitch & Winocur, 2002).

In contrast, non-executive abilities such as procedural memory, vocabulary, and numeric abilities are relatively spared by the aging process (Basak, Boot, Voss, & Kramer, 2008). For example, Jurado and Rosselli (2007) reported that age-related declines are diminished in less complex tasks and that older adults tend to perform well on tasks on which they have had substantial experience. Given that task complexity and its executive requirements are thought to be positively correlated (Luciana et al., 2005) whereas experience with a task will reduce its executive requirements (e.g., Fincham & Anderson, 2006), this finding supports the specific vulnerability of executive processes to age-related declines.

Whether specific EF components are differentially vulnerable to age-related declines remains to be determined. Decrements in either WM capacity or processing speed have been offered as explanations for age-related decline. For example, older adults perform as well as younger adults in a modified WCST that reduces the WM demands (Hartman, Bolton, & Fehnel, 2001). Furthermore, Salthouse, Fristoe, and Rhee (1996) removed much of the age differences in WCST performance by accounting for differences in processing speed. Alternatively, Dempster (1992) argued that deterioration of an inhibition mechanism (i.e., resistance to interference), as opposed to a more domain-general decline in either capacity or processing speed, may underlie age-related change in a variety of tasks, including the WCST. Older adults, similar to children, tend to make perseverative errors (i.e., choosing a previous category despite negative feedback), which may indicate an inability to inhibit an activated response pattern. Because WM and inhibition are so entwined (Roberts & Pennington, 1996), it may be difficult to determine whether one or the other is more affected by age-related declines.

In accord with the specific vulnerability of EF, normal aging is not characterized by widespread neural changes but instead by selective cell loss, dendritic deterioration, and chemical dysregulation in the PFC and hippocampus (Burke & Barnes, 2006). One longitudinal study that assessed non-demented older adults over 4 years revealed that gray and white matter loss was greatest in frontal regions (Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003). There also are changes in neurotransmission, notably that of dopamine (DA). Bäckman et al. (2006) reviewed evidence indicating significant loss of DA markers in the striatum, a subcortical region rich in dopaminergic neurons, and in several extra-striatal regions including the PFC. Based on a small yet consistent body of research, the authors suggested that DA loss may mediate age-related decline on tasks requiring fast and efficient solutions to novel problems, that is, executive tasks. Braver and Barch (2002) employed a computational model to test the notion that DA specifically provides a gating mechanism to regulate the updating and maintenance of context information in the dorsolateral PFC (DL-PFC). The authors suggest that with age DA projections to the DL-PFC are disrupted, causing impairments to the gating mechanism. Importantly, they purport that such disruptions would equally impair WM and inhibition, which supports the finding that performance on a variety of executive tasks deteriorates with age.

Finally, aging research has employed functional neuroimaging techniques to characterize changes in functional brain activity underlying executive abilities. Braver and Barch (2002) reported a generalized increase in task-related neural activity in older adults compared to young adults on a Continuous Performance Test (CPT), perhaps as the result of compensatory neural activation. However, the specific patterns of activity within the DL-PFC on that same task were moderated by trial type. At short delays, activity was greater in older adults, but at long delays, activity was diminished in older participants. The authors interpreted this finding as indicating impairments to the maintenance function of the DL-PFC. Colcombe, Kramer, Erickson, and Scalf (2005) also reported evidence of increased frontal activation in older participants on a executive task (Flanker task), but, in examining individual differences, found that greater activation was related to poorer task performance instead of better performance. Thus, it is possible that increased activation may not necessarily be compensatory but act as an impediment in some cases. Together, these functional neuroimaging studies point to the complexity of the neural correlates of EF: Although it is likely that the aging brain responds differently to task demands than the younger brain, it is not simply that widespread activation equals compensatory activation.

Conclusions

This overview of the development of specific domains of executive functioning documents improvement beyond the preschool years. Although the specifics of the developmental trajectory depend both on the complexity of the task and the scoring method, it appears that inhibition shows prominent improvement during the preschool years and less change later on. WM and shifting, on the other hand, appear to emerge in the preschool years but really improve the most afterwards in a more linear fashion. Planning ability, which typically is measured by more complex tasks, seems to make the largest gains in later childhood or adolescence. After requiring such an extended period to mature, EF is particularly vulnerable to the aging process as multiple executive processes (e.g., resistance to interference, WM) begin to show impairment by the 7th decade of life. Considering these general findings, previous reviews that omit EF development after age 5 ignore a substantial portion of the developmental story. Ideally, future research would examine broad age ranges that cover the entire lifespan.

Uses of executive function in daily life

After age 5, two main changes in children's lives are entry into a) more social settings and b) schooling, both of which require increased self control. Studies with older children have permitted research on associations between EF and children's functioning in these domains.

Social functioning and emotional control

The same general brain structures appear to underlie both cognitive and emotional processing. For example, the anterior cingulate cortex (ACC) has a cognitive subdivision that has interconnections with the prefrontal cortex, and an affective subdivision that has interconnections with the orbitofrontal cortex, amygdala, and hippocampus (Bell & Wolfe, 2004). These two subdivisions are intricately bound in cognitive tasks (Bell & Wolfe, 2004; Bush, Luu, & Posner, 2000; Casey et al., 1997; Davis, Bruce, Snyder, & Nelson, 2003; Wolfe & Bell, 2004). The link between one aspect of self-regulation, *effortful control*, and EF is likely due to the development of the anterior attention network (Rothbart, 2007; Rothbart & Bates, 1998). The construct of effortful control includes three major factors assessed by the Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001) that have been found to be especially related to EF: Attentional control (capacity to focus and shift attention), inhibitory control (the capacity to plan future action and suppress inappropriate responses), and low-intensity pleasure (derived from activities that are low in novelty, complexity, and intensity).

As evidence of connections between cognitive and emotional-behavioral control, in 7-year-olds, inhibition on a Stroop-like task is related to parent-reported inhibitory control in daily life (González, Fuentes, Carranza, & Estévez, 2001). Moreover, Wolfe and Bell (2004) found that 8-year-olds' self-report of activation control in daily life (i.e., the capacity to perform an action despite a strong tendency to avoid it) predicted performance on WM and inhibitory tasks (Bell et al., 2007). Also, their self-rating of high-intensity pleasure was negatively related to performance on these tasks. Other evidence is that the ability to inhibit on a flanker task predicted parent-reported effortful control in children aged 7–10 (Simonds, Kieras, Rueda, & Rothbart, 2007) and adolescents (Ellis, 2002, reported in Simonds et al., 2007). Finally, deficits in effortful control in middle childhood predict EF in adolescence. The lack of attentional control (i.e., attentional problems such as inattention, hyperactivity, and impulsivity) in school-age children (7–14 years-old) predicted EF (specifically WM updating, response inhibiting and to a lesser extent shifting) at age 17 (Friedman et al., 2007). It is promising that attention training programs may improve children's cognitive and emotional regulation (Rueda, Posner, & Rothbart, 2005).

In addition to effortful control, several other aspects of social-emotional development are related to EF. The ability to resist temptation and focus on the task in a delay-of-gratification task during the preschool years predicts better performance on an inhibitory (i.e., Go/No-go) task 14 years later during late adolescence (Eigsti et al., 2006). Moreover, psychosocial maturity (encompassing self-reliance, identity, and work orientation) is significantly related to adolescents' EF performance as measured by the Color Trails Test 2, which assesses shifting, sequencing, and divided attention (Galambos, MacDonald, Naphtali, Cohen, & de Frias, 2005). Steinberg (2007) argued that inhibition deficits may be particularly problematic during adolescence and contribute to adolescents' risk-taking behaviors. Finally, decreases in suggestibility (as measured using misleading questions regarding a video; Roebers & Schneider, 2005) and susceptibility to advertising (Moses & Baldwin, 2005) are also related to EF.

The link between EF and social functioning continues during aging. With old age the decrements to EF extend beyond the realm of pure cognition to negatively affect social functioning. For example, age-related increases in overt prejudice, social inappropriateness, depression, and problem gambling have been linked to EF declines (von Hippel, 2007).

Thus, EF appears to be related to social and emotional self regulation. What needs to be clarified, however, is the causal relation between the two during development. Does each spur the development of the other? It is critical to include children older than age 5 in order to detect long-term, perhaps even delayed, effects from early childhood.

School performance

The orchestration of foundational EFs appears to facilitate complex problem solving in school. Researchers have investigated both the concurrent relations between school functioning and EF and the predictive relations between the two. In general, the associations between EF and academic achievement are significant, though usually moderate, and, notably, persist as late as the sixth grade (Jacobson & Pianta, 2007) or perhaps even later when EF is well developed (Jarvis & Gathercole, 2003).

One method to examine this relation is to identify children with deficits in a particular academic area and compare their EF to that of normal children. In the domain of math, Blair and Razza (2007) found that inhibitory control, as measured by a peg-tapping task (e.g., tap once if experimenter taps twice and vice versa), was related to math ability in a group of low income kindergarteners. Similarly, Bull and Scerif (2001) found that 7-year-olds with lower math ability showed poorer inhibition (indicated by greater Stroop interference), difficulty switching from a learned strategy to a new strategy (indicated by increased perseverative responses on the WCST; see also Bull, Johnston, & Roy, 1999), and lower WM capacities (measured by counting span). St. Clair-Thompson and Gathercole (2006) also found an association between math achievement and WM and inhibition in 11- and 12-year-olds. Taken together, these studies suggest that children who have difficulty maintaining pertinent information in WM, ignoring irrelevant information, and switching from one strategy to another have difficulty using and evaluating strategies to solve math problems. What these studies lack, though, is a precise description of the relationship between EF processes and specific math abilities or operations, rather than general math abilities.

Some insight in this regard comes from two studies. Kroesbergen, van Luit, and Naglieri (2003) used the Cognitive Assessment System (CAS; Naglieri & Das, 1997) to examine associations between specific math skills and cognitive—including executive—functioning. Deficits in basic math skills were related to lower performance on all CAS scales (Planning [EF], Attention, Successive, and Simultaneous Processes), while automaticity deficits (i.e., lack of memorized multiplication facts) were related to poorer performance on the Planning, Attention and Successive scales. Moreover, deficits in word problem solving were associated with deficits in Attention and Successive processing. In a study looking at both accuracy and speed, different EF components accounted for children's (aged 6–13) and young adults' accuracy versus speed in a task entailing switching between simple addition and subtraction (e.g., $5 + 3 = \_\_\_$, $9 - 2 = \_\_\_\_$; Ellefson, Johnstone, Blagrove, & Chater, 2006). Efficiency in shifting accounted for most of the variance in accuracy, whereas inhibition and age accounted for most of the variance in speed. In sum, different aspects of EF relate to different aspects of math performance.

Deficits in EF have also been implicated in difficulties in reading. Protopapas, Archonti, and Skaloumbakas (2007) found that a sample of Greek 7th grade children diagnosed with dyslexia showed poorer inhibition (i.e., Stroop interference), and, among non-dyslexic children, slower reading speed was associated with greater interference. Only certain aspects of dyslexia may be implicated, however. van der Schoot, Licht, Horsley, and Sergeant (2000) found that children aged 9–12 characterized as dyslexic guessers (i.e., children diagnosed with dyslexia who spelled words quickly but inaccurately) showed greater Stroop interference and more incorrect moves on the TOL. Importantly, dyslexic spellers (i.e., children diagnosed with dyslexia who spelled words very slowly but accurately) did not demonstrate the same inhibition impairments. This suggests that poor inhibition is not directly related to dyslexia *per se*, but that it may exacerbate the problems related to dyslexia, such as spelling words inaccurately.

Deficits in EF domains have also been related to poor writing. Hooper, Swartz, Wakely, de Kruif, and Montgomery (2002) found reliable differences in EF between 4th and 5th graders characterized as good writers versus poor writers as measured by performance on a narrative writing task. Poor writers showed lower performance on tasks of initiation and set-shifting, though the between-group effect sizes were small (.16 and .13, respectively). An intervention that emphasized the problem-solving aspects of writing (e.g., the need for a plan and the procedural nature of writing) improved writing, though the results were modest (Hooper, Wakely, de Kruif, & Swartz, 2006). Thus, emphasis on the EF aspects of writing may improve children's writing skills. One common procedural aspect of writing entails taking notes on an assigned text and then writing a report based on those notes. Different EF components were found to contribute to the note-taking and note utilization tasks in 3rd and 5th graders (Altemeier, Jones, Abbott, & Berninger, 2006). Inhibition was related to note-taking for both grades, whereas planning (on the Tower of Hanoi task) contributed to the ability of 3rd graders, but not 5th graders, to utilize their notes in writing a report. Even as late as age 11 and 12, WM and inhibition are related to English (and science) scores (St. Clair-Thompson & Gathercole, 2006).

Riggs, Blair, and Greenberg (2003) examined the relations between EF and classroom behaviors (assessed on the Child Behavioral Checklist) likely to affect school achievement. For children ages 6–9, better inhibitory control, measured by the Stroop color word task and the Coding subtest of the

WISC-R (cracking a code by matching symbols to corresponding letters or numbers; Wechsler, 1974), was associated with fewer externalizing behaviors (i.e., aggressive or otherwise inappropriate behavior reported by the teacher) one year later, but was unrelated to their concurrent externalizing behavior. The researchers suggest a ''developmental lag;'' that is, the cognitive capacity for inhibition may develop prior to the external behavioral patterns associated with it. An EF skill may be expressed first in simple, structured settings (e.g., a quiet laboratory) before complex, real-life ones (e.g., the classroom or playground), which may explain more generally the unclear relations between EF as measured by neuropsychological tasks and EF manifested in school behavior. The notion of a developmental lag underscores the importance of including school-age children to explore the later effects of individual differences in preschoolers' EF. Longitudinal studies, though rare, are essential for detecting these relations.

What is the causal relation between EF and academic performance? One hypothesis is that EF directly affects academic performance. Poor WM obviously would hamper remembering instructions, performing mental calculations, and many other foundational academic tasks. Inhibition and shifting likely are important for ignoring irrelevant information and moving from one task to another. A second hypothesis is that the relation is less direct and has its effects through language skills or reasoning ability. For example, poor WM is associated with specific language impairment (Im-Bolter, Johnson, & Pascual-Leone, 2006), which in turn could hinder performance in many academic domains. Moreover, 10-year-olds' WM and inhibition is related to their ability to reason (Handley, Capon, Beveridge, Dennis, & Evans, 2004). Reasoning involves simultaneously holding in mind and manipulating representations. Most interesting in this study was that inhibition predicted logical thinking only when the content contradicted what one believed to be true. Handley et al. interpreted this finding as showing that reasoning requires resisting a prepotent response based on one's own beliefs and instead focusing on the logical structure of the logic problem. Since school settings require good language skills and decontextualized reasoning, these skills plausibly mediate between EF and academic success.

A third hypothesis is that more molar behaviors in the classroom could mediate the relations between EF and scores on academic tests. Standardized assessments consisting of rating scales can measure a variety of classroom behaviors that involve EF. Waber, Gerber, Turcios, Wagner, and Forbes (2006), using the Behavioral Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000), found that teacher ratings of these behaviors correlated with end-of-grade state-mandated achievement test scores, and correlated more highly than did the neuropsychological measures. The authors suggested that there may be a dissociation between laboratory and observational assessment, with each providing unique information about children's EF.

The above discussion focused on how EF might affect school performance. However, schooling in turn may facilitate EF development by providing situations that encourage EF practice (e.g., problem solving tasks; classroom environments that require inhibited behavior). McCrea, Mueller, and Parrila (1999) found moderate support for the influence of schooling on EF development: Third graders performed better on the Thurston Word Fluency Test, a test requiring mental flexibility (shifting), planning and monitoring, than did second graders of the same age. This effect of schooling was not found for grades 1 vs. 2, or 3 vs. 4. However there were no significant differences in WCST performance between any of the grade levels.

Several studies have examined effects of type of school—urban (Waber et al., 2006) and private vs. public (Ardila, Rosselli, Matute, & Guajardo, 2005)—on EF. However, confounding with parental education and income, and other demographics, make these studies inconclusive.

New methods are particularly needed to study the causal link between EF and academic achievement. For example, some of the standard laboratory assessments of EF could be adapted to include math content, which would bridge the EF and math assessments and identify the *specific* aspects of math that are most clearly related to EF. Also, comparisons of EF levels across cultures, like those done with preschool children (e.g., Sabbagh et al., 2006), might identify schooling and parenting practices that train EFs. Such studies have not been done with school-age children, to our knowledge, even though such experiences would likely have as much or more impact on school-age children's academic achievement as that of preschoolers.

In summary, by expanding EF research to school-age children, the relations to an important aspect of childhood—schooling—can be examined. Different academic activities (e.g., mathematics, reading, and writing) appear to involve different combinations of EF components. Attempts to uncover causality between EF and school functioning have been inconclusive. Likewise, more research is needed to reveal the contextual factors (e.g., type of classroom environment) that enhance EF. Once these relations are clarified, interventions can be developed to bolster the specific EF domains underlying each academic skill (Fischer & Daley, 2007).

Conclusions and directions for future research

A focus on the development of EF after age 5, as children enter a broader array of social contexts, builds on the preschool work to tell a fuller developmental story about EF. We organize our conclusions around the three themes of this paper introduced in the Introduction and suggest directions for future research on each.

EF as a construct

Regarding the question of whether EF is a single or multiple construct, concurrences in when components emerge and undergo rapid change would suggest that they are part of the same ability, or at least very closely related. We do know that the specific relations among the various EF components change across development, which suggests that the components are somewhat separate, even though related. How closely related are the EF components during the grade school and adolescent years? As previously mentioned, factor analysis of performance on multiple EF tasks suggests that the EF components are moderately correlated but separable. Moreover, there appears to be neural support for this unity-but-diversity view of EF. Although most EF tasks rely on activation in the PFC and ACC, the exact region of activation varies across tasks intended to tap different EF domains.

Future research could employ a training study design in order to address whether EF consists of largely independent components or a single, unified ability. Here, the researcher would train one EF component and then observe whether there are immediate changes in other components as well (see Klingberg et al., 2005, though with children with ADHD). Depending on the degree of carryover effects (i.e., how much other components benefit from the training), the researcher would draw conclusions about the degree of independence of EF components.

The preschool research has generated several theories about EF as a construct, including theorizing about the processes underlying EF development (e.g., Bunch, Andrews, & Halford, 2007; Zelazo, Müller, & Frye, 2003). For example, Zelazo's Cognitive Complexity and Control (CCC) theory emphasizes children's increasing ability to process more complex rule systems (e.g., Zelazo, Qu, & Müller, 2005). Also, Garon et al. (2008) view EF as a central attention system that is involved in all EF component operations. They propose that changes in EF during the late preschool period are due to the development of attention and integration of component EFs. Are these theories of early EF development relevant for addressing development later on in middle childhood and adolescence, and declines during aging? For the most part, the theories of early EF development have not been applied to older children, adolescents, and elderly adults. Tests of these theories with broader age groups could either strengthen them by expanding their scope to larger age groups or support revisions to account for findings across the broadened age range.

Developmental trajectories of each EF component

The study of EF development in young children has provided much important information about when EF processes emerge and are reliably used, for example, the rapid development of inhibition between age 3 and 5. Our review of subsequent developments shows continued improvement of all components, probably even into adolescence, as well as somewhat different developmental trajectories for each component. Though rudimentary forms of each EF domain may emerge early in life, they do not become fully functional until much later. Then, during aging, declines specific to EF emerge.

However, we know much less about this later development. Particular sorts of studies with school-age children and elderly adults would be especially useful for examining key questions about development. Examining several EF components in the same study over a wide age range would clarify the differing developmental trajectories of the components. Much of our knowledge is uncertain because it comes from piecing together multiple studies that vary in a number of ways. Better yet would be long-term longitudinal research, though it has high cost in money, time, and participant attrition. Adding neuroimaging assessments would be important as well for examining developmental trajectories. One longitudinal study (Gogtay et al., 2004) has described gray matter development in the brain through adolescence; however, how that development corresponds to behavior is not clear. Concurrences in rapid changes in brain functioning and cognitive performance would clarify how brain development underpins cognitive development.

Information about developmental trajectories is important for addressing several developmental issues. For example, they clarify why children of different ages differ in the particular components of EF they find difficult to recruit. Inhibition is both essential and particularly challenging during early childhood; older children and adolescents are less susceptible to distraction and less impulsive. Moreover, the sequence in which the EF components emerge (e.g., inhibition before planning) suggests possible causal relations among components during development.

Uses of EF in daily life

Research on this topic with young children has focused on the links between EF and emergence of theory of mind. Oddly, there appears to be little work regarding the EF–ToM relation in nonclinical populations of school-age children, even though ToM continues to develop during this period. The few studies found in our literature search had only a small control group of normal children to compare with children with disorders (e.g., autism, ADHD), the focus of the studies. In a typical study, Fahie and Symons (2003) found a significant correlation ($r = .68$) between a composite measure of EF and ToM in 5–9 year-olds referred to an outpatient clinic for behavioral problems. Moreover, they found that the relationship between social problems and EF remained after ToM was partialled out but that the social problems and ToM were unrelated after partialling out EF. Hence, they concluded that EF may underlie both ToM and social problems.

This possible link of EF to social problems is interesting because although peer relationships are known to become increasingly important during middle childhood and adolescence, we know little about the connections between EF and peer interaction. For example, is the ability to bracket (inhibit) one's own perspective and take another person's perspective (shifting) and hold both in mind and compare the two (WM) related to social understanding and effective social interaction?

The work on older children expands the domains for which EF might be important, in particular, formal schooling. This review suggests that, although the relationship is far from clear, the EF components appear to be related differentially to various academic subjects. One possible, largely ignored, mediator between EF and school performance is learning strategies, particularly strategies believed to be involved in memory. We probably know more about children's memory and memory strategies than any other aspect of cognitive development. One component of EF, WM, obviously should be closely aligned with memory development more generally, and thus might involve memory strategies already researched. In both children and adults, inhibition and updating of WM, but not shifting, are related to monitoring performance in a time-based prospective memory task (Mäntylä, Carelli, & Forman, 2007). Moreover, source (contextual) memory and avoiding false memories are related to WM and inhibition in 6, 8, and 10 year-old children (Ruffman, Rustin, Garnham, & Parkin, 2001). It is likely that the development of EF, metamemory, and strategies are closely related during the school age years.

EF also may contribute to children's variability in strategy use. It is possible that children acquire the ability to inhibit less effective strategies in favor of new, more effective strategies and that children's ability to formulate a plan is closely related to the selection of effective strategies. Finally, one conclusion from the memory literature is the importance of children's growing knowledge base and the deep knowledge base of elderly adults. The role, in EF performance, of knowledge about the relevant content area seems important to examine.

The correlates of EF and other abilities and behaviors not only suggest the applications of EF (how EF causes X) to daily living but also can give clues about the developmental processes causing the development of EF (what X's cause EF). The cognitive, biological and social correlates of EF and how they change from one age to another after age 5 would provide clues as to whether different developmental processes are contributing to the development of EF at different ages. For example, it may be that biological development—especially brain maturation—is particularly important in young children, especially for inhibition, whereas environmental factors affect EF more so in older children. For example, language (e.g., Kray, Eber, & Lindenberger, 2004) and opportunities for physical activity (Davis et al., 2007, in press; Tomporowski, Davis, Miller, & Naglieri, 2008) appear to contribute to EF development in school-age children. Still other contributors to EF development need to be explored. For example, young adults (age 20–29) experiencing one night's sleep deprivation showed impaired executive functioning, in comparison to a control group (Nilsson et al., 2005). Perhaps then the detriment in academic performance in sleep-deprived children could be attributed at least in part to impaired executive attention. Thus, studying children older than age 5 may enhance our understanding of EF by broadening the potential causes and outcomes that are examined.

In conclusion, more research and theorizing on EF in children older than five would provide a more complete picture of the development of EF. Such work would shift the research focus from the early emergence of EF to its refinement and application to daily life. By examining the existing research on children after age 5 we have attempted to transform what currently is a scattered, non-integrated body of work on school-age children into a coherent framework that would help construct a strong, developmental account of an important cognitive achievement. Converging evidence from cognitive, behavioral, and neural assessments during childhood provides exciting new information about EF development.

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