The Emergence of Cognitive Control Abilities in Childhood

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Abstract Cognitive control, otherwise known as executive function, refers to our ability to flexibly adjust or regulate habitual actions or behaviors. As a cluster of separable components, it depends heavily on the prefrontal cortex, one of the last brain regions to reach adult maturity. Cognitive control processes are thought to be among the key factors for scholastic success, and thus, underdeveloped cognitive control abilities might contribute to an achievement gap. In this chapter, we first discuss the prolonged maturation of the prefrontal cortex that leads to delayed emergence of cognitive control abilities in children. We briefly describe some of the functional effects of prolonged maturation of the prefrontal cortex. We then discuss how experience and environmental factors such as education and socio-economic status may affect the development of cognitive control abilities, before turning to cognitive training interventions as a promising avenue for reducing this cognitive “gap” in both healthy children and those with developmental disabilities. Taken together, our hope is that by understanding the interaction of brain development, environmental factors, and the promise of cognitive interventions in children, this knowledge can help to both guide educational achievement and inform educational policy.

Keywords Executive function · Socioeconomic status · Hypofrontality · Cognitive intervention · Plasticity

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1 Introduction

A bicyclist in Maryland has the freedom to legally occupy the center of a full street lane. This freedom confers a number of advantages, but most importantly, it’s the safest place for a cyclist to ride. That is, when bicyclists travel as far to the right as practicable, they risk being missed as drivers pull out of side streets and driveways. A Maryland bicyclist transported to New York, then, encounters some immediate problems. In New York, the law forbids bicyclists from occupying a full street lane, relegating them to shoulders and sidewalks. Our brave Maryland bicyclist must quickly shift cycling behavior in order to abide by New York law and avoid a costly ticket (or worse).

The scenario that we have described above is a real-world illustration of cognitive control—also known as executive function (EF)—and it refers to our ability to flexibly adjust or regulate habitual actions or behaviors. An essential component to higher cognition, this ability allows us to successfully navigate our surroundings, overriding habitual behaviors and routines when current task goals or demands require otherwise. The prefrontal cortex (PFC) has been associated with cognitive control function by acting to guide the selection of task-relevant actions during information processing (Miller and Cohen 2001; Shimamura 2000). Several features of the PFC—including its distinctive anatomy, wide range of inputs and outputs to other cortical regions, and its neuromodulatory regulation of other brain systems—contribute to a role for the PFC in directing and regulating behavior (Miller and Cohen 2001).

Cognitive control is not a single process but rather, refers to a cluster of separable components that collectively work to guide goal-directed behavior (Botvinick et al. 2001; Miller and Cohen 2001; Norman and Shallice 1986). Such components can include self-regulation and self-awareness, task-switching, updating, and response inhibition (Barkley 2001; Friedman and Miyake 2004; Miyake 2000). It is thought that these components can operate over a wide variety of domains including selective attention, working memory (WM), and language processing (Badre and Wagner 2007; Novick et al. 2005; Smith and Jonides 1999; Thompson-Schill et al. 2005). As illustrated in Fig. 1, neuroimaging and
Neuropsychological studies have demonstrated that cognitive control processes recruit regions of prefrontal cortex (PFC), including dorsolateral and ventrolateral prefrontal cortices (e.g., Jonides et al. 2008; Novick et al. 2009; Thompson-Schill et al. 1997), as well as regions of anterior cingulate cortex (e.g., Miller and Cohen 2001, Botvinick et al. 1999). Recent evidence has challenged the notion that cognitive control and its components remain fixed once we reach adulthood (e.g., Gray and Thompson 2004); rather, these cognitive processes may in fact be malleable and amenable to interventions. In order to better understand the mechanisms underlying these processes, it is important to first understand the development of these processes during childhood. Because these control processes are thought to be key factors for scholastic success, underdeveloped cognitive control abilities might lead to an achievement gap (e.g., Gathercole et al. 2004; Pickering 2006).

In this chapter, we will outline the current literature on the role that cognitive control (or lack thereof) plays from a developmental perspective. First, we will briefly summarize the literature on the neuroanatomical development of the brain in childhood. Then, we will discuss (1) the effects of an immature prefrontal cortex on behavior, (2) how environmental factors can influence cognitive control during
development, and (3) how targeted cognitive interventions may serve to demonstrate the malleability of cognitive control, having longitudinal implications for educational achievement. We then conclude by highlighting outstanding issues for the field to address.

2 The Developing Brain

Primates, including humans, are born with immature brains, and it has been well established that brain maturation develops throughout childhood and adolescence (e.g., Gogtay et al. 2004; Sowell et al. 2003). Throughout post-natal development, the neocortex matures through an initial, rapid growth process of cell proliferation and changes in synaptic density. During this period, the increase in synaptic connections accompanies dendritic and axonal growth (i.e., fibers for communication that extend from neurons) and myelination (i.e., insulation, thus boosting signal transmission) of the subcortical white matter (Huttenlocher and Dabholkar 1997). Synaptogenesis is then followed by pruning, a synapse elimination process that lasts well into the third decade of life (Huttenlocher and Dabholkar 1997; Petanjek et al. 2011). Critically, rather than occurring concurrently throughout the whole brain as they do in rhesus monkeys (e.g., Rakic et al. 1986), these processes dynamically occur at differing rates throughout the brain in humans (Huttenlocher and Dabholkar 1997). Brain regions subserving sensory functions, such as vision and hearing, develop first, followed by development of temporal and parietal cortices, regions responsible for sensory associations. Higher order cognition areas, such as prefrontal and lateral temporal cortices, which serve to integrate information from primary sensorimotor cortices and modulate other cognitive processes, appear to mature last (Casey et al. 2005b; Petanjek et al. 2011).

Boosted by the development of noninvasive neuroimaging technologies in the last two decades, researchers have learned a great deal about the anatomical and functional networks of the developing brain. Early work with positron emission tomography (PET) imaging demonstrated that human PFC metabolizes glucose at a slower rate, relative to occipital, temporal, and parietal cortices (Chugani and Phelps 1986). This result suggests that early development prioritizes basic human survival functions rather than higher order cognitive processes. More recently, structural imaging studies have demonstrated that over the course of development, cortical gray matter loss (i.e., a signature of cortical maturation after puberty) occurs earliest in primary sensorimotor areas and last in dorsolateral prefrontal and lateral temporal regions (Gogtay et al. 2004). Moreover, there appears to be evidence for a “fine-tuning” of cortical structures as activation shifts from diffuse to focal recruitment as children develop (Brown et al. 2005). Taken together, structural and functional evidence suggests that prefrontal regions associated with integration and goal-directed behaviors mature after regions responsible for primary sensory functions (Casey et al. 2005a), with both progressive and regressive processes (rather than simple linear patterns of change) underlying changes in cognitive abilities (Amso and Casey 2006; Brown et al. 2005).
3 Functional Consequences of an Immature Prefrontal Cortex

There are behavioral and functional consequences of these anatomical developments in children, and most prominently, children exhibit deficits in cognitive control which has been attributed to the immaturity of the cortical networks subserving those control systems. For example, in laboratory tasks, children are more susceptible to interference from competing information and actions as compared to adults (Casey et al. 2002; Morton and Munakata 2002). Concretely, infants fail at delayed-response paradigms such as the “A-not-B” task, in which they indicate whether an occluded object is in the same location as previously observed (e.g., Diamond 1985). In adults, cognitive control is classically measured with the Stroop task (Stroop 1935), in which participants must inhibit reading habits in order to indicate the word’s ink color (e.g., “red” written in blue ink). In children, cognitive control can be assessed with Stroop-like tasks, including a day/night task (in which subjects say “day” when they see a black card with a moon and stars, and “night” when they see a white card with a bright sun), or the red/blue dog task, in which subjects say “red” when they see a blue dog and “blue” when they see a red dog (Beveridge et al. 2002; Gerstadt et al. 1994; Nilsen and Graham 2009). In particular, 6-year olds make more errors on this task (e.g., calling the dog by its color rather than by its name) than 8-year olds (Beveridge et al. 2002). In addition to these cognitive factors, self-regulative processes (e.g., achievement-related behavior, personal strivings, and regulating shared goals in close relationships) are important to childhood development (Blair and Diamond 2008; Hofmann et al. 2012). Individual differences in emotional self-regulation can account for academic achievement beyond what can be explained by general intelligence (Blair and Razza 2007). The development of self-regulation in children may be mediated by an interaction of top-down executive control and bottom-up influences of emotion and stress reactivity (Ursache et al. 2012), playing a role in successful social and emotional competence (Blair 2002). Taken together, this brief summary shows that as a result of prolonged maturation of prefrontal cortex (relative to other parts of the brain which reach adult maturity sooner), children exhibit impaired behavioral and cognitive control for years (Thompson-Schill et al. 2009).

How do the neurobiological signatures of cognitive control differ between children and adults? In one seminal study by Casey and colleagues (Casey et al. 1997), children and adults both performed a go/no-go task while undergoing functional magnetic resonance imaging (fMRI). In the go/no-go task, participants are instructed to either respond (on go trials) or withhold a response (on no-go trials). The authors found that activity in the anterior cingulate cortex and ventral prefrontal regions correlated with error rate (i.e., false alarms, or responding when told to withhold responding). Notably, exhibiting more false alarms than adults, children activated prefrontal cortex (specifically, dorsolateral prefrontal cortex, or DLPFC) more diffusely than adults during the task, but DLPFC activation did not
correlate with task performance. These results suggest that maturation of the prefrontal cortex involves reduction of diffuse activity in the form of both strengthened relevant connections, as well as attenuated irrelevant connections (Casey et al. 1997; Hare and Casey 2005).

Using a flanker task to test interference resolution and response inhibition (Eriksen and Eriksen 1974), Bunge and colleagues (Bunge et al. 2002) found that immature cognitive control abilities were associated with the inability of children to recruit ventrolateral prefrontal cortex (VLPFC) regions in a similar manner to adults, that is—children failed to activate a region in right VLPFC that was recruited for multiple types of cognitive control by adults. Other fMRI studies have found that subcortical systems—specifically, the striatum—may also play an important role in overriding inappropriate responses (Booth et al. 2003; Durston et al. 2002). Specifically, lower activity in the caudate nucleus parallels poorer performance on a go/no-go task in children and adolescents (Durston et al. 2003; Rubia et al. 1999).

In addition to spatial differences in the anatomical substrates subserving cognitive control in children and adults, some research suggests age-related differences in temporal dynamics as well. Wendelken and colleagues (Wendelken et al. 2012) administered a task manipulating rule type, rule switching, and stimulus incongruency to both children and adults. That is, in a task that asked subjects to indicate color or direction of a stimulus on any given trial, consecutive trials could switch the given rule (i.e., a switch from indicating color to indicating direction). Both participant groups activated a brain network related to cognitive control, including posterior parietal cortex, left dorsolateral prefrontal cortex (DLPFC), pre-motor cortex (PMC), and the anterior portion of the supplementary motor area (pre-SMA); see Fig. 1. However, the temporal dynamics demonstrated that DLPFC activation in children reflected the previous rule type (regardless of the current rule), suggesting “sluggishness” in executive function shifting abilities. Whether a similar pattern might emerge in other cognitive control regions requires further study, but behavioral data suggest the persistence of a similar “carry-over” effect observed in children but not adults (Crone et al. 2006a).

Other noninvasive imaging technologies, including diffusor tensor imaging (DTI), can map structural connectivity across brain regions. In one study, Liston and colleagues (Liston et al. 2006) found that the degree of connectivity between prefrontal cortex and striatum (both linked to cognitive control task performance as described earlier) correlated positively with age. However, in comparing the frontostriatal tract to a second fiber tract (i.e., the corticospinal fiber, which also correlated with age), only frontostriatal connectivity predicted go/no-go task performance. This result indicates that maturation of frontostriatal connectivity (as indexed by DTI measures) contributes to the development of cognitive control abilities. Taken together, these findings suggest that a combination of structural and functional information gained from noninvasive brain technology can inform us about the developing brain and how it affects cognitive control systems.

As outlined above, there are clearly negative consequences to the prolonged development and maturation of the prefrontal cortex in children. We have
described a number of studies showing that across a variety of cognitive control paradigms, children exhibit poorer performance relative to adults. Conversely, there might be an evolutionary advantage to the late development of prefrontal cortices and the cognitive control network. What might be the nature of this advantage? There may be positive consequences to this lack of cognitive control during childhood (Chrysikou et al. 2011; Thompson-Schill et al. 2009), wherein an immature frontal cortex (sometimes referred to as hypofrontality) might confer adaptive benefits. Thus, there may exist a trade-off between a system tuned to optimal performance (i.e., rule-based), versus a system built for learning (i.e., data-driven). A testable prediction for this proposal is that children should outperform their older counterparts on some cognitive tasks, and this is indeed the case, most prominently in the domain of language acquisition and language learning (e.g., Gleitman et al. 1984). For example, in noun pluralization, Ramscar and Yarlett (2007) demonstrated that children are easily able to master irregular plurals (e.g., mouse → mice) rather than adopting a pluralization dictated by the more frequent convention (e.g., mouse → mouses). This result points to the idea that children maximize probabilistic input, which in this case, optimizes performance. In contrast, adults tend to rely on a probabilistic approach by monitoring the probabilities of alternative patterns (Ramscar and Yarlett 2007). This age-related difference in learning (observed in domains such as language learning) may be promoted by a lack of cognitive flexibility driven by an underdeveloped prefrontal cortex.

On the other hand, the hypofrontality as observed in children may have other consequences in the domain of language comprehension. In particular, consider the incremental nature of language processing—that is, the notion that we interpret language as it unfolds in real time, rather than awaiting the end of the sentence. As such, readers (and listeners) commit to an initial interpretation and anticipate arriving information. One consequence of this incremental processing is temporary ambiguity in parsing decisions—in cases where an initial interpretation turns out to be wrong, subjects must revise their initial interpretations in order to arrive at the correct meaning of the sentence. This process triggers cognitive control abilities, as subjects detect a need to recover from misanalysis (Novick et al. 2005). 5-year olds, relative to 8-year olds and healthy adults, demonstrate a failure to revise in these initial parsing decisions (e.g., Trueswell et al. 1999), paralleling performance observed in patients with left PFC damage (Novick et al. 2009).

As a final example, consider the case of functional fixedness, a bias in which participants are hindered in reaching a solution to a problem because of their knowledge of an object’s conventional use. In a classic laboratory problem solving task, participants must indicate that a box can be used to reach an object high on the shelf (i.e., a height booster), rather than (conventionally) used as an object for containing things. German and Defeyter (2000) found that when the conventional use of the box was initially demonstrated, older children (7-years old) took longer to arrive at the solution compared to when the conventional use was not demonstrated. Notably, younger children (5-years old) had comparable performance, regardless of whether the object’s conventional use was demonstrated or not. This “immunity” to functional fixedness at an early age suggests that older children
were more likely to apply a “rule” to the box’s use, resulting in longer solution times (or failing to arrive at the correct solution at all). There are other cases when a lack or reduction of cognitive control permits cognitive flexibility, particularly in the domain of creativity. That is, a lowered state of cognitive control might allow adults to reduce the filtering properties of the PFC (e.g., Shimamura 2000), thus promoting a more data-driven rather than a rule-based approach to the cognitive task at hand. Chrysikou and Thompson-Schill (2011) did just this using an fMRI paradigm. For each object in a set, young adults generated common uses (e.g., shoe as foot apparel) or uncommon-but-plausible uses (e.g., shoe as hammer) for the object. Common object use generation reliably activated prefrontal cortex, whereas uncommon object use reliably activated regions of occipito-temporal cortex. Further, perceptually based responses (e.g., using a chair for firewood, which does not require prior knowledge of a chair’s function) predicted activation in posterior cortex, suggesting that a diminished state of cognitive control may, in fact, confer benefits to certain creativity tasks.

In sum, these results demonstrate that an immature prefrontal cortex bears negative consequences on some cognitive domains, but that it can also provide benefits toward other cognitive domains. In particular, hypofrontality may have positive consequences for tasks in which data-driven learning, rather than rule-based performance, drives optimal performance (Chrysikou et al. 2011; Thompson-Schill et al. 2009). Considering this trade-off, the argument for accelerating maturation of cognitive control networks that are mediated by regions of prefrontal cortices may need to be tempered with the evolutionary advantages that immature frontal lobes may confer.

4 Environmental Factors in Cognitive Control Development

Recent work posits an important influence of environmental factors, including socioeconomic status (SES), on the developing brain. SES, a composite measure, considers economic and non-economic factors, including material wealth, social prestige, and education. Educational advocates have long discussed the negative implications of low SES backgrounds on cognition, and ultimately, on academic achievement. Moreover, SES correlates with life stress and neighborhood quality, and previous work has shown that low SES children suffer from poorer health, impaired psychological well-being, and impaired development throughout the lifespan. These consequences point to a role for SES in shaping candidate neural pathways by which SES might compromise academic achievement or increase the risk of mental illness (see Hackman et al. 2010 or Hackman and Farah 2009 for review). Because neurobiological systems may mediate these SES-cognition gradients, we focus here on work demonstrating a link between SES and assessments of cognitive control, executive function, and language. For example, Noble and colleagues (Noble et al. 2005) found that in kindergarteners of differing SES
backgrounds, low SES children performed worse than middle SES children on language (mediated by the left perisylvian regions) and EF (mediated by the prefrontal cortex) measures. The groups did not differ on the other cognitive measures, and the authors point to the delayed maturation of the brain regions mediating these abilities as being more susceptible to environmental factors (like SES). A subsequent study of individual differences using a population of first-graders demonstrated that SES explained 30% of the variance in language performance (Noble et al. 2007). SES also explained 6% of the variance in both cognitive control and working memory performance (despite the small value, this value was statistically significant in both cases).

While the role of SES has been examined in sociological and epidemiological contexts, research is just now beginning to shed light on its impact on neurobiological mechanisms. A network of regions mediates reading processes, including left hemisphere middle temporal and inferior frontal gyri, and left-posterior superior temporal sulci (Turkeltaub et al. 2003). SES can modulate activity in these regions during reading. Specifically, there is a negative correlation between the brain-behavioral relationship and SES levels in these regions, with an amplified impact of SES at lower SES levels (Noble et al. 2006b). Indeed, there appears to be a systematic effect of SES on reading skills (even after controlling for other factors), suggesting a multiplicative effect of reading ability and SES that exaggerates poorer performance at low SES levels (Noble et al. 2006a). Further, EEG measures indicate that SES modulates measures of attention, with low SES children showing an attenuated response to novel stimuli relative to high SES children (Kishiyama et al. 2009), and a reduced ability to inhibit distractors (D’Angiulli et al. 2008; Stevens et al. 2009). In 5-year-old children, SES predicts hemispheric asymmetry of the inferior frontal gyrus (even after controlling for scores on a standardized set of language and cognition tests), with left lateralization associated with higher SES (Raizada et al. 2008). In line with this result, Sheridan and colleagues (Sheridan et al. 2012) found that right medial frontal gyrus activity was inversely related to accuracy in acquiring a novel stimulus–response association (e.g., through a dimensional change card sorting task). Moreover, Raizada and colleagues (Raizada et al. 2008) also found that SES trended toward predicting both white and gray matter volume in these regions, suggesting anatomical consequences to SES variation.

In sum, these results suggest that SES variation results in altered prefrontal anatomy, with negative consequences on various cognitive domains, particularly those subserving language and executive function. On the other hand, the susceptibility of prefrontal cortices to experiential and environmental factors suggests that these cortical networks might be malleable. Indeed, there is evidence from naturalistic experiments showing that schooling can promote cognitive control beyond natural development. For example, Burrage et al. (2008) have demonstrated that schooling had a significant impact on executive function in a group of prekindergarten and kindergarten children when compared to children at the same age which did not attend school. In light of these findings, there exists the potential for targeted educational interventions to enrich the neural architecture of the child.
in order to give rise to enhanced cognitive function. In particular, these interventions might be especially beneficial for children who are facing learning difficulties or who come from low SES backgrounds. Thus, although factors such as low SES might result in an educational achievement gap, timely educational interventions may be able to minimize or even close this gap. We turn now to the research that has explored this possibility.

5 Cognitive Interventions from a Developmental Perspective

Conventionally, cognitive training is defined as a means of improving cognitive functioning through practice and/or instruction (Jolles and Crone 2012). A rapidly emerging field concerns the impact of cognitive training (and in particular, WM training) on transfer measures of cognitive control, EF abilities, and general fluid intelligence in adults (e.g., Jaeggi et al. 2008; see Morrison and Chein 2011 or Hussey and Novick 2012 for recent reviews on the topic). Our focus here is on cognitive training studies from a developmental perspective. Cognitive training studies in children can take many forms (e.g., mindfulness training, and core or supplemental curricula—see Diamond and Lee 2011), but in this chapter, we focus on cognitive interventions in the form of computerized games that specifically target WM and EF processes. For example, an early study used an adaptive (i.e., adjusting for difficulty as the participant’s performance improved) and intense (i.e., repeated several times a week for at least five weeks) intervention in a child population with attention deficit hyperactivity disorder (ADHD), characterized by inattention, impulsivity, and hyperactivity (Barkley 1997) and linked to impaired function of the frontal lobes (for review, see Castellanos and Proal 2012). In addition to improving on the trained WM task, participants significantly improved on an untrained WM task, as well as on Raven’s Progressive Matrices (RPM), a non-verbal complex reasoning task (Klingberg et al. 2002). A subsequent study demonstrated that across measures of WM (items successfully remembered in spanboard and digit span), EF (Stroop task completion time), and complex reasoning (correct RPM items), ADHD children that trained on computerized WM tasks outperformed those children completing a control training program (Klingberg et al. 2005). Some of these effects persisted three months after the end of training, suggesting that long-term changes are possible with short, intense training periods.

Since then, other studies have used such intervention paradigms in children in order to improve EF and WM abilities through training. These studies have used paradigms targeting attention (Rueda et al. 2005), WM (Holmes et al. 2009; Jaeggi et al. 2011; Loosli et al. 2012; Thorell et al. 2009), inhibition (Thorell et al. 2009), and reasoning (Bergman Nutley et al. 2011; Mackey et al. 2011). Some of these studies have examined intervention paradigms in the context of ameliorating developmental disabilities, including ADHD (Hoekzema et al. 2010); developmental dyscalculia (Kucian et al. 2011), reading abilities in at-risk youth (Yamada
et al. 2011), and dyslexia (Temple et al. 2003). Such interventions generally demonstrate improvement on executive functions and cognitive control—that is, those skills that are critical for scholastic achievement (e.g., Diamond and Lee 2011). Additionally, these interventions may interact with environmental factors, such as SES. In one study, low-SES children trained on either reasoning (e.g., “Rush Hour”) or speed (e.g., “Blink”) processing using a battery of commercially available games. Post-training results suggested that both processes are separately modifiable with improvements seen in a special population that may need the intervention the most (Mackey et al. 2011).

Though the results of the studies described above are promising, there is much variability in terms of training length, frequency, and assessment type across the various designs of intervention studies in children. Thus, in order to best understand the mechanisms underlying training and transfer of EF and WM abilities, further work is necessary (Buschkuehl et al. 2012; Jaeggi et al. 2011, 2012; Shah et al. 2012). The underlying neural mechanisms are beginning to be addressed in adults (e.g., Dahlin et al. 2008), but only a handful of studies have looked at the neural correlates underlying cognitive interventions in children. As a result, the neural mechanisms that lead to the observed neural changes and plasticity are still unclear. That is, some studies report decreased changes in activation following training (Haier et al. 2009; Kucian et al. 2011; Qin et al. 2004), whereas others report increases in activation following training (Hoekzema et al. 2010; Jolles et al. 2012; Shaywitz et al. 2004; Stevens et al. 2008; Temple et al. 2003). At least one study has examined structural changes in the form of cortical thickness differences after training (Haier et al. 2009), though the authors note that there was no overlap between regions showing functional changes and those showing structural changes, suggesting a complex relationship that warrants further study.

These mixed findings point to an array of results that seek to demonstrate how the brain changes after cognitive training. Decreased activation after training suggests increased processing efficiency or performance of the task within capacity limits (cf. Nyberg et al. 2009), whereas increased activation might reflect additional recruitment of neural resources. A combination of these two patterns could represent a re-distribution of neural activity after training, whereas activation in different brain regions (i.e., brain regions not active pre-intervention) would reflect qualitative changes in brain activity that could represent a change in strategy (Buschkuehl et al. 2012; Jolles and Crone 2012). In general, future cognitive training studies that can incorporate a neuroimaging component are necessary in order to better understand the neural mechanisms (i.e., understanding the how) underlying training and transfer. Researchers also have to keep in mind that age might moderate the outcomes of intervention studies. For example, although variable training (i.e., training in which there are novel task demands in each training session) can boost transfer effects in adults, this variability can also hinder those same desired effects in children (Karbach and Kray 2009). Thus, researchers have to keep in mind that just because cognitive training paradigm shows promise in adults, that does not mean that the same will be true for children—the child brain is not necessarily a “miniature version” of the adult brain. It is possible that
while training in adults may modify existing neural architecture, training in young children may influence the construction of that architecture (Galvan 2010), suggesting qualitative and quantitative differences across children and adults (Jolles and Crone 2012). For example, during the delay period of a WM task (i.e., when no stimulus is present, but participants manipulate the to-be-remembered information), children (8 to 12-year olds) failed to recruit right DLPFC and bilateral superior parietal cortex, whereas young adults did activate this region (Crone et al. 2006b). Thus, it may be possible to boost recruitment of this region during WM manipulation with a cognitive training paradigm, particularly since intensive cognitive training in younger individuals may actually lead to more widespread transfer effects, possibly due to the unspecialized state of functional neural networks at a younger age (Wass et al. 2012).

What makes an intervention effective, and how can previous research inform the optimized development of future intervention studies, particularly in children? Diamond and Lee (2011) offer some suggestions, including promoting motivation, repeated practice, challenging tasks that engage children, the inclusion of aerobic exercise, and other elements of the intervention that provide children with a sense of joy and acceptance.

6 Open Questions and Suggestions for Future Research

Several open questions remain as we work to more fully understand cognitive development as an interplay amongst (a) anatomical and functional changes of the brain throughout childhood and adolescence, (b) environmental factors, and (c) targeted interventions that may boost cognitive control processes (cf. Fig. 2). Given the progressive and regressive development of the child and adolescent brain, cognitive intervention studies that combine behavioral and neuroimaging measures may provide a better understanding the cognitive and neural mechanisms underlying cognitive control in the context of other factors.

Moreover, there is likely an important role of individual differences in terms of cognitive control and the extent of its susceptibility to intervention. Previous research has demonstrated training-related individual differences (e.g., Jaeggi et al. 2011; Rueda et al. 2005), and we have also reviewed a role for environmental factors (i.e., SES, which will also vary by individual) in cognitive control, and finally, developmental disabilities may also determine training outcome. In considering and designing intervention studies, then, we suggest that researchers give serious thought to the role that these environmental factors and individual differences may play in the effects of training and transfer, as well as their underlying mechanisms.

Finally, in spite of the interventions that seek to reduce or even close an achievement gap from those who exhibit poorer EF skills than others, there may also exist a fine balance between hastening frontal lobe development through cognitive interventions in order to improve cognitive control and EF, and allowing
an immature prefrontal cortex to confer cognitive benefits (Thompson-Schill et al. 2009). Nonetheless, reducing the achievement gap, particularly for those children at an economic disadvantage or with developmental disabilities, is of critical interest for our educational system. We will need a better developed and characterized understanding of the interaction of prefrontal maturation, learning, and cognitive control in order to guide research and inform educational policy.

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