Executive functioning (EF) refers to a set of higher order cognitive processes that are integral to many everyday psychological activities, including planning, inhibition, flexible thinking, and focused attention. Clinical and brain imaging studies suggest these higher order cognitive abilities are supported in part by the prefrontal cortex (PFC), a large area at the front of the brain that has evolved rapidly over the last 3 to 5 million years and is protracted in its developmental time course. This chapter will examine the close association of PFC development and changes in higher order cognitive functioning that occur in early childhood, and discuss new findings that suggest the PFC is part of a larger executive functioning network.

THE DEVELOPMENT OF EXECUTIVE FUNCTIONING

EF develops into early adulthood, but it shows particularly pronounced change in infancy and childhood (for reviews, see Diamond, 2002; Morton, 2010). These changes can be readily observed when watching infants and children try to solve simple problems that require planning, inhibition, and flexible thinking. In the A not B task, for example, 8- to 12-month-old infants learn to retrieve a toy hidden at a nearby location called "A." Then, the same toy is hidden in a new "B" location. Even though infants watch as the toy is hidden at B, most perseverate by searching for the toy at A. This striking behavior was first observed by Jean Piaget, who maintained it reflected a fragile understanding of objects as things that exist independently of one's own actions. However, more nuanced experiments revealed that infants search for the toy at A despite some memory of it being hidden at B, suggesting difficulty inhibiting reaches to A. Preschool-aged children show comparable behaviors. In the Dimensional Change Card Sort (DCCS), for example,

3-year-old children sort colored shapes (e.g., red trucks and blue flowers) one way (e.g., by shape) and then are asked to switch and sort the same cards in a new way (i.e., by color). Although children this age can answer basic questions about the new rules (e.g., "Where do the red cards go in the color game?"), most will persist in sorting cards the old way. As was true in the A not B task, children appear to have the requisite knowledge for succeeding, but they cannot voluntarily bring about a change in their behavior.

There is, of course, a very spirited debate about exactly what aspect of EF is changing during this period, and how these changes might be tied to other aspects of development (for discussion, see Morton, 2010). It is conceivable, for example, that infants and children have only a vague recollection of what they were previously shown or told to do, and therefore are prone to falter when such memories compete with stronger habitual responses (Morton & Munakata, 2002; Munakata, 1998). Alternatively, infants and children may remember exactly what they were shown or told, but falter because of an immature ability to inhibit incorrect behaviors (Kirkham, Cruess, & Diamond, 2003). Finally, children may be able to remember but not reflect on what they know (Zelazo, Mueller, Frye, & Marcovitch, 2003). Regardless, there is some consensus that the ability to plan, inhibit inappropriate behaviors, and focus on what is at hand are aspects of cognitive functioning that follow a protracted developmental time course. The prevailing question then is why—why do these abilities develop so slowly?

EXECUTIVE FUNCTIONS AND THE DEVELOPMENT OF THE PREFRONTAL CORTEX

One prominent hypothesis has argued that an important constraint on the development of EF abilities is the maturation of the lateral prefrontal cortex (PFC; Bunge & Zelazo, 2006; Dempster, 1992; Diamond, 2002). The PFC is well suited to perform cognitive control tasks, is important for the completion of EF tasks in adults, and it follows a more protracted course of development than other brain areas. Both lesion and functional magnetic resonance imaging (fMRI) studies suggest that the development of the PFC plays a pivotal role in the acquisition of executive functioning abilities with age.

The lateral PFC is located anterior to the precentral sulcus and comprises one third of the human cortex. It occupies a larger portion of the cortex in humans than in other animals, suggesting it may play a role in implementing those behaviors that make us distinctly human, such as executive functions (Miller, Freedman, & Wallis, 2002). The PFC sends and receives projections from association areas, virtually all sensory and motor systems, and from a number of subcortical structures (Miller & Cohen, 2001; Tanji & Hoshi, 2008). Due to its vast range of anatomical connections, the PFC is capable of synthesizing information from a wide array of brain structures, making it a suitable candidate for EF implementation.

An intact PFC is necessary for the successful completion of EF tasks. Patients with lesions to the PFC have greater difficulty performing the Stroop task

(Perret, 1974; Vendrell et al., 1995), the go/no-go task (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003), and the Wisconsin Card Sorting Task (Milner, 1963) than do controls or patients with lesions to other parts of the cortex. Patients with dorsolateral prefrontal cortex (DLPFC) lesions have great difficulty shifting from one sorting criterion to another as the demands of the task change when performing the WCST (Milner, 1963). Similarly, when virtual lesions are created over the lateral PFC, performance is disrupted on such tasks of switching (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006a), as well as on tasks of inhibition (Vanderhasselt et al., 2006b) and working memory (Koch et al., 2005). These virtual lesions are created using transcranial magnetic stimulation (TMS), which involves the passing of a pulse of current through a coil placed over the head which generates a magnetic field. The magnetic stimulation of a particular brain area, such as the lateral PFC, disrupts whatever processing is occurring in that region (Pascual-Leone, Walsh, & Rothwell, 2000). Finally, the importance of the lateral PFC for EF has also been demonstrated using fMRI. An increase in activation in the PFC is evident during the performance of working memory (Petrides, 2000), task switching (Lie, Specht, Marshall, & Fink, 2006), and inhibition tasks (Aarts, Roelofs, & van Turennout, 2009). These divergent methods all suggest that the lateral PFC plays a vital role in EF performance in adults.

Although it is clear that the PFC plays a role in EF, of particular interest is whether the maturation of this brain region coincides with and influences EF development. Convergent evidence from studies examining developmental changes in synaptogenesis and gray and white matter suggest that this is indeed the case. Synaptogenesis involves the process of synapse formation and maintenance and is necessary for the establishment of efficient communication between neurons (Cohen-Cory, 2002). Following birth there is a stage of rapid synapse production with synaptic density increasing greatly in the first year of life. Synaptic pruning then follows, eliminating unnecessary synapses and resulting in an overall decrease in synaptic density during childhood and adolescence (Huttenlocher, 1979; Huttenlocher, de Courten, Garey, & Van der Loos, 1982). This maturational process is different in different areas of the cortex. In primary sensory areas, synaptogenesis occurs early with the maximum amount of synapses existing between 3 and 6 months of age. Synaptic elimination then begins at age 1 and mature levels of synaptic density are reached in these areas before the age of 12. The PFC, however, acquires synapses at a much slower rate, with synaptic density peaking between the age of 2 and 3. Synaptic elimination does not begin in the PFC until age 7 and continues until adult levels of synaptic density are achieved in midadolescence (Huttenlocher, 1999). This protracted developmental trajectory of synaptogenesis in the PFC corresponds nicely to that of the development of EF abilities, suggesting that synaptogenesis may be one factor contributing to the maturation of EF skills.

In concert with these developmental changes in synaptic density, there are also changes in gray matter thickness across development. Gray matter consists primarily of densely packed neuronal cell bodies and dendrites (Kalat, 2007; Mason, 2011). To determine the amount of gray matter in each region of the brain, a

measure of gray matter density is taken. This measure is obtained by creating a sphere with a 15 mm radius at each cortical surface point. The proportion of gray matter in that small region is calculated to index local cortical thickness (O'Hare & Sowell, 2008; Sowell, Thompson, Tessner, & Toga, 2001). The study of gray matter density and thickness can be made in vivo using magnetic resonance imaging (MRI) technology. MRI has the capability of distinguishing between gray and white matter so that they can be measured and studied separately. The different types of tissues that comprise gray and white matter behave differently when stimulated, and this information can be used to make three-dimensional images of the tissues (Ward, 2010).

A significant amount of gray matter density loss occurs between adolescence and adulthood with a loss of approximately 32% between the ages of 7 and 60 (Sowell et al., 2001, 2003; Takahashi, Ishii, Takigi, & Yokoyama, 2011). Gray matter density follows a nonlinear pattern with age akin to synaptogenesis (Sowell et al., 2001). In most regions of the cortex, gray matter volume increases at younger ages, with gray matter loss commencing around puberty and a stabilization of cortical thickness occurring in adulthood (Giedd et al., 1999; Gogtay et al., 2004; Shaw et al., 2008). This gray matter thinning reflects maturation of the cortex and is beneficial for performance on cognitive tasks. Children with greater cortical thinning in the left dorsal frontal and parietal lobes display better performance on measures of verbal intelligence (Sowell et al., 2004).

Like synaptogenesis, gray matter loss also follows a different trajectory in different regions of the cortex. Reductions in gray matter density occur in the parietal cortices early on in childhood, between age 4 and 8. As development progresses, these reductions extend into temporal regions and finally reach the dorsal PFC toward the end of adolescence. The frontal lobe, the area of the brain implicated in higher order processing such as EF, is the last area of the brain to mature. In contrast, those areas of the brain associated with more basic functions like early sensory and motor areas begin their maturation much earlier (Gogtay et al., 2004; Sowell et al., 2001).

Concurrent with developmental changes in gray matter are developmental changes in white matter microstructure. White matter consists primarily of myelinated axons. In order for information to travel through the nervous system, it is carried between neurons by these axons (Kalat, 2007; Mason, 2011). White matter in the brain is studied using diffusion tensor imaging (DTI). This technique allows us to look at the movement of water in the brain, allowing for the examination of anatomical connectivity between regions. The integrity of white matter tracts is assessed using fractional anisotropy (FA), which is a measure of the directionality of water diffusion. FA scores offer information on the diameter, density, and myelination of white matter, with higher FA values indicating more coherent white matter tracts (Barnea-Goraly et al., 2005; Olesen, Nagy, Westerberg, & Klingberg, 2003; Snook, Paulson, Roy, Phillips, & Beaulieu, 2005).

In contrast to the nonlinear pattern seen across development with synaptic and gray matter density, a linear pattern exists when white matter development is considered. The volume of white matter in the brain increases linearly with age with

a net increase of 12.4% between the ages of 4 and 22 (Giedd et al., 1999; Sowell et al., 2003). Similarly, FA values increase with age in several cortical regions, including the PFC, basal ganglia, thalamus, and corpus collosum (Barnea-Goraly et al., 2005). Maturation of white matter in the frontal lobe continues well into the second decade of life (Barnea-Goraly et al., 2005; Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999). This protracted nature of white matter maturation offers the possibility that myelination is also playing an important role in the development of cognitive abilities, which also have a protracted developmental time course.

The development of mature white matter tracts is linked to improvements in EF performance. Diffusion in frontostriatal tracts becomes more restricted with age, and these developmental changes are related to performance on a go/no-go task. Frontostriatal tracts with more restricted diffusivities are associated with obtaining faster reaction times in the task (Liston et al., 2006). Similarly, higher FA scores in both the left superior and inferior frontal lobe are correlated with better performance on a working memory task (Nagy, Westerberg, & Klingberg, 2004). These results suggest that improvement on EF tasks may in part be due to more myelinated or coherent white matter circuits in the frontal lobes.

It is evident that the maturation of the brain follows a protracted course of development with the frontal lobes taking the longest period of time to mature. Both gray and white matter in the PFC do not fully develop until well into adolescence. Similarly, performance on EF tasks continues to improve well into the second decade of life. The existence of this similarity in developmental trajectories has led to a great deal of research dedicated to looking at this relationship in more depth. Studies examining age-related differences in brain functioning during the performance of EF tasks do suggest that these two developmental processes appear to be tightly linked. fMRI is used to elucidate such functional changes. By tracking changes in blood oxygenation, fMRI provides a means of imaging the functioning brain in vivo. This technique is safe and noninvasive and therefore has been used to study brain functioning in infants and young children (Casey, Davidson, & Rosen, 2002; Davidson, Thomas, & Casey, 2003). Studies using this technique have found age-related changes in PFC functioning, with increases in lateral PFC activity with age during Stroop (Adleman et al., 2002) and working memory performance (Bunge & Wright, 2007; Klingberg, Forssberg, & Westerberg, 2002; Kwon, Reiss, & Menon, 2002). Others have found decreases in PFC activity (Casey et al., 1997) or changes in the laterality of PFC activation with development on response inhibition tasks (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002).

There is some inconsistency regarding exactly how the PFC is functionally changing across development and how these changes are influencing the development of EF. Developmental neuroimaging studies face a variety of challenges during data collection which may be impacting the differences that are seen in their results. One of the difficulties these researchers face is accounting for motion artifacts. fMRI images are sensitive to artifacts produced if the participant moves during the experiment. Even small movements of the neck or head can have a

significant impact on the quality of the images produced. Data collection generally takes at least an hour, and it can be difficult for young children to remain still for so long (Davidson et al., 2003). A useful alternative to these lengthy studies would be to use resting state data to look at developmental changes in the brain as such data takes less than 10 minutes to collect while the child rests in the scanner. This method will be discussed in more detail as a useful alternative to examining developmental brain changes and their relationship to the development of EF.

One criticism of the lateral PFC account of EF development is that it focuses on developmental changes in one brain region while neglecting changes in other potentially important brain areas. The PFC is not the only region of the brain that shows functional changes with development. Coinciding with developmental improvements in response inhibition, brain activation increases progressively with age in parietal, striatal, cerebellar, and thalamic regions in addition to the PFC (Luna et al., 2001). Similarly, task switching is associated with a distributed frontal parietal network rather than a single localized brain region. Differences are seen with age not only in the PFC, where children show an effect of dimension shifting in the right superior frontal sulcus, but also in the superior parietal cortex and thalamus. These regions are more active in adults than children during dimension shifts of attention (Morton, Bosma, & Ansari, 2009). Given that executive functioning is associated with activity in many brain regions, it is possible, in principle, that the development of EF is related to changes in the functional integrity of a distributed network rather than a single brain region.

The lateral PFC clearly plays an important role in EF. It is activated during most executive functioning tasks, and lesions to this area generally result in difficulties on such tasks. However, results from the neuroimaging literature suggest that it is not the PFC alone that is responsible for EF. Developmental functional changes are also seen in other areas of the brain. It is important to move away from this modular view of brain functioning and instead consider the development of brain networks involved in EF. This may help us develop a better understanding of the relationship between brain development and the development of EF.

A NETWORK APPROACH

To explore the relationship between EF and brain development, it is imperative that the entire network of neural regions implicated in EF is examined. A network of brain regions exists that subserves EF. This network is composed of the anterior cingulate cortex, presupplementary motor area, DLPFC, inferior frontal junction, anterior insular cortex, dorsal premotor cortex, and the posterior parietal cortex (Cole & Schneider, 2007). During the performance of EF tasks, these regions interact, showing high correlations with each other but not with other regions of the cortex. It is the interaction of these regions that allows us to perform EF tasks successfully.

Activity in these EF regions is coactivated not just during task performance but also at rest (Cole & Schneider, 2007). Examining the correlations between activity in

brain regions while participants are at rest has become a popular method for examining cortical networks in children and is known as resting state functional connectivity MRI (rs-fcMRI). Collecting rs-fcMRI from children is simple: It takes less than 10 minutes and no complicated task instructions are required. The short time period required to collect rs-fcMRI data mitigates the motion issues that accompany standard task-related fMRI data collection. Resting state data are of interest because whether one is at rest or engaged in a task, the brain is exhibiting slow blood oxygen level–dependent (BOLD) fluctuations in the range of 0.01–0.1 Hz (Vogel, Power, Petersen, & Schlagger, 2010). These fluctuations are correlated in brain regions that are functionally connected and are thought to reflect the history of coactivity between the regions (Biswal, Yetkin, Haughton, & Hyde, 1995; Vogel et al., 2010). Looking at the development of this EF network may shed new light on the relationship between brain development and the development of EF.

Along with age-related structural brain changes, changes also take place in functional networks across development (Dosenbach et al., 2010; Fair et al., 2007, 2009; Kelly et al., 2009; Stevens, Kiehl, Pearlson, & Calhoun, 2007; Supekar, Musen, & Menon, 2009; Vogel et al., 2010). A consistent finding across developmental rs-fcMRI studies is that brain networks in children are organized by anatomical proximity, with strong short-range functional connections, whereas in adults these networks are organized in a more distributed way across the brain, showing enhanced long-range connections (Vogel et al., 2010). The development of these networks follows a protracted course, with adolescents showing connectivity patterns falling in between those of children and adults (Kelly et al., 2009). This developmental pattern of changing brain connectivity is so reliable that rs-fcMRI data can be used to predict an individual's brain maturity (Dosenbach et al., 2010). It is clear that, overall, brain networks seem to change across development, but are there developmental changes in the EF network specifically?

To address this question, rs-fcMRI has been used to examine changes in connectivity between only those regions involved in the performance of cognitive control tasks. Such control in adults is implemented by two brain networks: the frontoparietal network, which is important for adaptive control; and the cinguloopercular network, which implements task-set maintenance (Dosenbach et al., 2007). When only those brain areas implicated in cognitive control are examined, developmental changes are seen in both of these networks (Fair et al., 2007). Across development, connections between frontal and parietal regions increase in strength, leading eventually to the frontoparietal control network seen in adults. The cinguloopercular network is relatively incomplete in childhood, with many connections missing and appearing only gradually with age. Overall, the pattern across development involves an increase in long-range connections and integration between regions, and a decrease in short-range connections with age, termed *segregation*. The development of adult cognitive control networks relies on these two principles of segregation and integration, and this may help explain the protracted course of developmental performance on EF tasks.

The increase in integration with age is likely contributed to by the myelination of long-distance axons allowing information to travel from distant neurons

at a faster rate. The development of white matter myelination follows a protracted course, and it is only in the second decade of life that these long-range connections are established in the brain. Synaptic pruning may contribute to the segregation which occurs with age as less efficient short-range connections are eliminated. It is evident that the lateral PFC alone is not responsible for performing EF tasks. Instead, a network of regions interacts to successfully accomplish such tasks. These functional networks change dramatically over the course of development. As such, it is important that we do not focus solely on the development of one important region in EF, but rather focus on the development of the network of regions that are involved in making EF possible.

SUMMARY AND CONCLUSION

Performance on EF tasks follows a protracted course of development with improvement occurring throughout childhood and adolescence. Following a similar time course is the development of the PFC. Changes in synaptic, gray matter, and white matter density continue to occur with age throughout the brain, but the PFC is the last brain region to reach maturity. Structural maturity in this brain region is not reached until adolescence, around the same time that EF abilities reach full development. Evidence from lesion, fMRI, and TMS studies consistently show the importance of the lateral PFC in the successful completion of EF tasks. Research examining the impact of PFC development on the development of EF abilities has neglected the consideration of developmental changes in other brain regions that are involved in EF. Examination of EF networks has revealed that they undergo extensive developmental changes, showing an increase in long-range connections and a decrease in short-range connections with age. It is likely that these changes in network architecture are contributing to the development of our abilities on EF tasks. Although there are still many research avenues to be explored to elucidate the developmental origins of EF, the study of brain networks may offer a useful avenue for quantifying the relationship between brain development and the maturation of executive functioning.

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