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Developmental implications of children's brain networks and learning

Abstract: The human brain works as a synergistic system where information exchanges between functional neuronal networks. Rudimentary networks are observed in the brain during infancy. In recent years, the question of how functional networks develop and mature in children has been a hotly discussed topic. In this review, we examined the developmental characteristics of functional networks and the impacts of skill training on children's brains. We first focused on the general rules of brain network development and on the typical and atypical development of children's brain networks. After that, we highlighted the essentials of neural plasticity and the effects of learning on brain network development. We also discussed two important theoretical and practical concerns in brain network training. Finally, we concluded by presenting the significance of network training in typically and atypically developed brains.

Keywords: brain disorders; brain network; *f*MRI; functional connectivity; human development; motor learning.

Introduction

Functional networks refer to networks consisting of mutually connected brain regions on which temporal

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patterns of neural activity are statistically dependent. Remote regions in the functional brain networks may not be physically connected. The communication between regions is dynamic and context-specific, depending both on subject and task characteristics (Stevens, 2009). Functional networks are usually identified with neuroimaging techniques when one is at rest. Among these techniques, resting-state functional magnetic resonance imaging (rs-*f*MRI) is the one that is most popular and most widely used (Ernst et al., 2015).

The rs-*f*MRI is suitable for identifying the intrinsic networks that reflect the spontaneous brain fluctuations resulting from the maturation of the neural systems (becoming more stable and adult-like), the prior history of co-activation between the brain regions, and the present neural activities (Johnson, 2011; Guerra-Carrillo et al., 2014). The identification of brain networks has become a key research area with the emergence of the rs-*f*MRI (Menon, 2013; Byrge et al., 2014), which has several advantages. Firstly, because no task is implemented during resting-state scans, it is free from the influences and constraints of the tasks (Nomi and Uddin, 2015). Secondly, it is relatively easy to acquire resting-state data from special populations, like infants and patients, who have difficulties in certain cognitive tasks. Moreover, exploratory or data-driven analyses can be conducted on rs-*f*MRI data with less biased information about brain anatomy and dynamics. Perhaps it is a more powerful way of uncovering new principles of brain organization (Ernst et al., 2015).

Studying brain networks from a developmental perspective carries significant implications. Brain network maturation occurs as one grows older, and it interacts with behavioral changes (Diamond, 2000; Johnson, 2011; Byrge et al., 2014). Besides, because some neuropathology occurs at system level, brain network studies can provide evidence to validate existing models and theories that describe neural changes underlying the emergence and progression of brain disorders (Menon, 2011; Ernst et al., 2015; Fornito et al., 2015). Therefore, the developmental view provides valuable insights into the psychopathological or neurodevelopmental mechanisms of brain disorders like autism spectrum disorders (ASDs) and attention deficit/hyperactivity disorder (ADHD) (Yan and Thomas,

2002). Investigating the network would help identify the biomarkers that differentiate typical and atypical neural development. This is particularly crucial for the early detection and diagnosis of developmental brain disorders.

To date, some intrinsic networks have been consistently reported, even in infants (Gao et al., 2015b). Research highlights the networks' importance in early human development in the mechanisms that help infants and children adapt to the world. Infant and adult networks mainly differ from each other in the number of connected voxels and the connectivity strength (Jolles et al., 2011). Primary examples of intrinsic networks include the sensorimotor network, the visual network, the attention network, the default mode network (DMN), the salience network, and the fronto-parietal network (Gao et al., 2015b; Supekar et al., 2009, 2010). We will discuss these studies in the following sections. According to Gao et al. (2015b), the connectivity strength between most of the networks decreases from 1 to 2 years of age, thereby demonstrating a trend towards network segregation during human development. The sequence of maturation differs between networks. The sequence starts from the sensorimotor/auditory network, then progresses to the visual network to attention/default-mode, and finally to the executive control networks during the first year of life (Gao et al., 2015a).

Because *f*MRI is susceptible to movement artifacts, we should be cautious when interpreting the rs-*f*MRI results of children and special populations (Power et al., 2015). In addition, the instructions for subjects in different studies might vary. Some might ask the subjects to close their eyes, whereas other might ask the subjects to stare at a fixation cross during scanning, leading to different behaviors in children and adults.

Developmental trajectories of functional networks in children

Sensorimotor networks

Sensory and motor networks have been observed in infants (Fransson et al., 2007). The sensorimotor networks primarily include the somatosensory area, the primary motor cortex, the secondary motor cortex, the supplementary motor cortex, and the premotor cortex (PM). It was first observed in brains of 41-week infants (Fransson et al., 2007). Liu et al. (2008) noticed greater intra-hemispheric connectivity than interhemispheric connectivity in the sensorimotor networks in infants of 12 months old.

Moreover, the connectivity strength of the sensorimotor networks increases from 1 to 2 years of age (Lin et al., 2008). However, as shown in a longitudinal study, the connectivity within the sensorimotor networks decreases during this period of time (Gao et al., 2015b).

Visual network

The visual network is mainly in the visual cortex. By using independent component analysis, the visual network can often be divided into several sub-networks due to the hierarchical structure of the visual cortex (Gohel and Biswal, 2015). This sensory network is present at birth (Doria et al., 2010), and it shows rapid development in the first 2 years of life (Lin et al., 2008). However, the connectivity between the visual system and the prefrontal cortex has not been observed in infants between 30 and 50 months old (Redcay et al., 2007), thus suggesting that the visual network is characterized by short-range connections during this period (Fransson et al., 2007).

Attention network

This network can be divided into two or three complementary parts according to two different categorization methods. It can be divided into the ventral and the dorsal attention networks (VAN and DAN) (Farrant and Uddin, 2015). The former is right-lateralized, consisting of the right ventral frontal cortex (VFC) and the temporal-parietal junction (TPJ); the latter includes the bilateral frontal eye field and the intraparietal sulcus. VAN and DAN are engaged in response to unexpected events (bottom-up attention) and goal-directed (top-down attention) processing, respectively (Farrant and Uddin, 2015). Farrant and Uddin (2015) compared the connectivity of DAN and VAN between children (7–12 years old) and adults (18–31 years old). They observed more within-network connections in the DAN and more internetwork connections between the VAN and the salience network in children; this suggests that there is a shift from the overrepresentation of exogenous stimuli to greater top-down attention control during human development. Recently, Cao et al. (2014a,b) reported an inverted U-shaped developmental trajectory of the DAN connectivity that matures at around 30 years of age. Consistent with this view, Casey and colleagues suggested that the DAN and language regions are the last regions to mature (Casey et al., 2000).

In another categorization, the attention network is divided into the alerting (frontal and parietal cortices), the orienting (TPJ and VFC), and the executive control

sub-networks (anterior cingulate cortex, ACC, and the lateral prefrontal cortex, LPFC) (Petersen and Posner, 2012; Wang et al., 2014a,b, 2015). It is noteworthy that the VAN and the orienting sub-network largely overlap each other and that they may share similar cognitive functions. It was proposed that the orienting sub-network appears in the early months of life and matures at 2–4 years of age (Posner et al., 2014a,b; Rothbart and Posner, 2015). Following this development, the executive control sub-network gradually differentiates from the orienting sub-network (Rothbart et al., 2011), and it has an inverted U-shaped developmental trajectory with a peak at about 4–7 years of age (Raz and Buhle, 2006; Fjell et al., 2012). The alerting sub-network has a steady developmental trajectory from infancy to adulthood (Rueda et al., 2004). This shows that the networks that support different aspects of attention mature at different rates.

Default mode network

The DMN is involved in social or self-referential processing, stimulus-independent thought, manipulation of episodic memories, and semantic knowledge (Hulvershorn et al., 2014). It includes the posterior cingulate cortex (PCC), the medial prefrontal cortex (MPFC), the medial temporal lobe (MTL), and the angular gyrus (Fox and Raichle, 2007). The DMN undergoes a steady developmental trajectory from infancy to adulthood. In the perinatal period, the anterior and posterior parts of the DMN are often found in different networks (Wylie et al., 2014). With participants from neonates to 2 years old, Gao et al. (2009) observed DMN development from a distributed network to an adult-like network. In a large sample study (210 participants of 7–31 years of age), Fair et al. (2008) reported that there were sparser connections within the DMN in children than in adults. Similarly, Supekar et al. (2010) scanned 45 persons from two age cohorts (7–9 vs. 19–22 years of age) and observed weaker DMN connectivity (especially between MPFC and PCC) in children. Consistent with this observation, Sherman et al. (2014) showed that the connectivity between PCC and MPFC increases from 10 to 13 years of age. From late adolescence to adulthood, the anti-correlation between DMN and task-positive networks increases (Barber et al., 2013). In general, the DMN becomes more and more integrated from teenage to adulthood (Fair et al., 2007, 2008).

Salience network

The salience network includes the ACC and the anterior insula (Seely et al., 2007). This network is important for orienting to and detecting the relevant stimuli. The connectivity increases within the salience network during the first year of life but decreases during the second year (Gao et al., 2015b). This may suggest that the salience network reaches its plateau connectivity during the first year of life and undergoes fine tuning thereafter. Because the salience network is involved in functions crucial for survival and learning, the early maturation of this network may enable rapid learning and threat avoidance during the early period of life.

Fronto-parietal network

The fronto-parietal network is regarded as the central executive network (CEN) consisting of the dorso-lateral prefrontal cortex (DLPFC) and the lateral posterior parietal cortex (Seely et al., 2007). This network is involved in higher cognition, ranging from working memory to decision making. During the first year of life, connectivity within the bilateral fronto-parietal network increases rapidly, and the rate of growth is reduced in the second year of life (Gao et al., 2015b). From 10 to 13 years of age, an increased connectivity between the DLPFC and other CEN nodes occurs, and there is greater segregation between the fronto-parietal network and the DMN (Sherman et al., 2014).

Patterns of development of functional networks

There are three dominant theories on brain development: maturation, skill learning, and interactive specialization (Johnson, 2001, 2011; Karmiloff-Smith, 2009; Jolles and Crone, 2012; Klingberg, 2014). The maturational view suggests that the brain is genetically pre-programmed to follow a certain sequence of structural maturation which underlies human development. This view interprets cognitive and motor development as a consequence of the maturation of specific regions of the brain. The skill-learning perspective suggests that the brain regions active in children are similar to those in adults; it also highlights the role of learning or training in promoting human development. The interactive specialization theory emphasizes that interregional interaction changes the functional characteristics of brain regions for human development. These general developmental theories indicate the essential role of the emergence and development of intrinsic brain networks in childhood development.

During development, neural pruning, axonal myelination, and behavior-brain interaction forge brain networks together. Brain networks emerge and evolve from more widely distributed and weaker ones to more focal, specialized, and stronger ones, from local connections to distant connections (Supekar et al., 2009; Hulvershorn et al., 2014). Some general requirements or rules about the transformation of the network organization from childhood to adulthood have been established (Figure 1) (Ernst et al., 2015).

The local to distributed pattern

During the prenatal period, short-range connections are abundant and characterize many local networks (Ernst et al., 2015). During development, two kinds of reorganization occur. One is an increase in long-range connections, such as links between the two hemispheres or between the anterior and the posterior parts of the brain. These distant connections improve the large-scale integration of information, making the brain a more dynamic and integrated system (Hwang et al., 2013). Meanwhile, smaller networks are refined, specialized, and restricted (Fair et al., 2007).

Network enhancement through experience

The Hebbian theory can be extended to a network level where the more certain functions are used in daily life, and these processes are more likely intensified in brain networks (Ernst et al., 2015). This highlights the importance of experience-based plasticity in network development. According to this view, the connections between the key regions are reinforced, whereas the redundant connections are reduced, thereby reorganizing brain networks from diffuse to more focal links (Durston et al., 2006; Stevens, 2009).

Network development through internetwork interaction

The hierarchical architecture is an important feature of a mature brain network. The formation of this architecture is driven by an integration of repeated experiences and relative biological scaffolding (Ernst et al., 2015). Along with the specialization of small networks, sub-networks emerge in childhood (Supekar et al., 2009). Accompanied by the development of long-range connections, smaller networks are reorganized into larger networks, thus
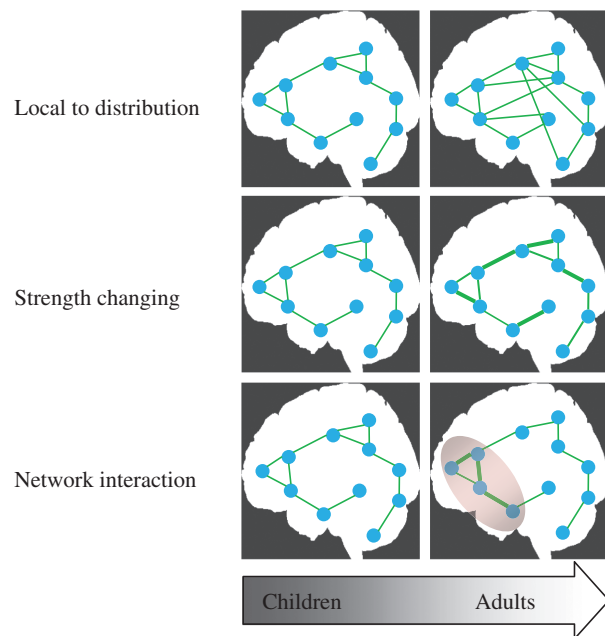

Figure 1: A schematic diagram for rules of network development.

forming a large-scale hierarchical architecture (Supekar et al., 2009; Ernst et al., 2015).

Typical network development

As a general rule, the sensory and motor networks are present at birth, whereas other networks engaging in higher-order cognition emerge later on (Stevens, 2009). The first reported brain networks include the visual, the auditory/temporal, the sensorimotor, the prefrontal cortex, the subcortical/basal ganglia, the parietal cortex, and the cerebellum networks (Fransson et al., 2007; Smyser et al., 2011). From infancy to adulthood, the network connectivity generally extends along the posterior-anterior direction; and the specialization and fine tuning of functional networks for higher cognition are still ongoing during early adolescence (Hoff et al., 2013).

Brain networks develop rapidly during the first 2 years of life. The strength of the connection increases with age, especially in the sensorimotor cortex and the PCC (Lin et al., 2008; Hulvershorn et al., 2014). Thalamic connectivity with the sensorimotor and salience networks is already present in neonates, whereas that with the visual and DMN networks emerges during the first year of life (Alcauter et al., 2014). Cortical hubs are largely confined to the sensory and the motor regions to support perception-action tasks during infancy (Fransson et al., 2011). Adult-like sensorimotor networks can sometimes be

observed in children aged 5–8 years old, whereas the DMN and other networks involved in higher cognition are not mature enough during this age range (de Bie et al., 2010). Compared to adults, children have weaker within-network connectivity in the salience network and the DMN, and weaker connectivity between the CEN and the salience network and between the salience network and the DMN (Menon, 2013).

In childhood, some adult-like networks are developed. Using the graph-theoretical approach, Supekar et al. (2009) observed significant small-worldness and hierarchical organization in 7- to 9-year-olds. The centrality of most nodes in the DMN and the dorsal anterior and posterior cingulate, the right anterior insula, and the left posterior temporal cortex in the CEN increases with age from 7 to 15 years of age, implying that these nodes become increasingly important during childhood development (Sato et al., 2014). In addition, functional network segregation and integration proceed from childhood to adulthood, which is characterized by an increase in distant networks and a decrease in local networks (Fair et al., 2009; Vogel et al., 2010; Damaraju et al., 2014). Another two manifestations of functional segregation and integration are a shift from the subcortical-cortical to the cortico-cortical connection (Supekar et al., 2009) and increased within-network connectivity and more efficient between-network connectivity (Stevens, 2009). Transition to adolescence is associated with the greater centrality of the angular gyrus and the lower centrality of the subcortical and cerebellar regions (Sato et al., 2015).

The development of the cognitive/executive control networks is an important mechanism underlying various issues in children and adolescents (Ernst et al., 2015). These networks are first seen in full-term and late-preterm infants (Doria et al., 2010). They continue to develop from childhood to late adolescence and early adulthood (Stevens, 2009). This process parallels the development of the neocortex and supports the view that the development of the higher-level integrative networks builds upon the earlier-developing networks (Luna and Sweeney, 2004; Stevens, 2009). Dosenbach et al. (2010) used functional connectivity in the cingulo-opercular network to predict brain maturation, and they found parallel development of the executive network and neocortex. The development of control networks is of importance for children and adolescents for whom a development lag would produce problematic or risky behaviors as well as developmental disorders (Somerville and Casey, 2010; Sripada et al., 2014a,b).

Kelly et al. (2009) examined the functional development of the ACC from childhood to adulthood. Sub-regions engaging in emotional and social information processing seem to have the greatest degree of development. The functional connectivity between the amygdala to most of the subcortical and limbic regions is stable from 4 to 23 years of age. However, its connection with the MPFC increases with age, whereas its connections with the insula, the superior temporal sulcus (STS), the parahippocampal gyrus, and the PCC show the reverse trend (Gabard-Durnam et al., 2014).

Another important issue is the development of anti-correlated networks. The anti-correlated networks are formed in the first year of life with further expansion by the age of 2 years (Gao et al., 2013). Chai et al. (2014) investigated the development of anti-correlated networks in 82 individuals of 8–24 years of age. The correlations of activity between the MPFC and the DLPFC and between the lateral parietal cortices and the DAN reversed from positive to negative with age increases. The correlation between these networks turns from positive in childhood into negative in adulthood (Chai et al., 2014). Sherman et al. (2014) examined the development of the DMN and the CEN in 45 children aged 10–13 years. They observed enhanced within-network connectivity and between-network segregation. The aforementioned evidence indicates that during childhood and adolescence, networks are becoming distinct from each other with increased anti-correlation.

Atypical network development

Autism spectrum disorders

Here we review atypical network development in several typical developmental disorders (ASDs, ADHD, and mood disorders). ASDs are prevalent neuro-developmental disorders marked by repetitive and restrictive behaviors and deficits in social interaction and communication. Compared to typically developing (TD) controls, ASD patients show both hypo-connectivity and hyper-connectivity in different networks (Uddin et al., 2013).

Firstly, most studies reported reduced connectivity in patients with ASDs, compared with TD patients. Inter-hemispheric connectivity in the sensorimotor cortex, the anterior insula, the fusiform gyrus, the superior temporal gyrus (STG), and the superior parietal lobule is reduced in ASD patients (Anderson et al., 2011). Most of the decreased connections are located in the DMN (Hernandez et al., 2015), the visual and the motor networks (Uddin et al., 2013), the thalamus (Nair et al., 2013), and the networks engaging in social-emotional information processing

(Hernandez et al., 2015). For the DMN, reduced connectivity was primarily reported between the posterior DMN (the inferior parietal lobe, IPL) and the superior frontal gyrus (SFG) (Wiggins et al., 2011) and between the precuneus and other DMN areas (Assaf et al., 2010). Weaker connectivity between the PCC and the SFG is related to poorer social functioning in ASD children (Monk et al., 2009). For the social-emotional networks, reduced connectivity was often observed between the posterior superior temporal sulcus (pSTS) and the reward-related brain regions (Abrams et al., 2013), between the striatal areas and the insula (Di Martino et al., 2011), and between the salience network and the MTL network (Ebisch et al., 2011; von dem Hagen et al., 2013). The decreasing connectivity of the insula with age in TD children is reversed in ASD children (Bos et al., 2014). In adults with ASD, there is reduced connectivity between the right pSTS and fronto-parietal areas typically encompassing the action observation network (Alaerts et al., 2014), and this may underlie their communication deficits.

Secondly, there was greater functional connectivity in patients with ASDs than TD in some connections. For example, Lynch et al. (2013) found increased functional connectivity between the PCC and the temporal cortex. Wiggins et al. (2011) observed a smaller increase of functional connectivity within the DMN in ASD patients. Moreover, stronger connectivity between the PCC and the right para-hippocampal gyrus is related to more severe repetitive behaviors in ASD children (Monk et al., 2009). Hyper-connectivity between the DMN and the salience network was also reported (Uddin et al., 2013).

Uddin et al. (2013) claimed that age can be a confounding factor in connectivity studies. Specifically, hypo-connectivity is often reported in adolescents and adults, whereas hyper-connectivity is often shown in children. However, this view has not been fully supported in recent reports. For instance, Padmanabhan et al. (2013) tested the atypical cortico-striatal connection in patients with ASD. They observed hyper-connectivity between the striatum and the parietal cortex but hypo-connectivity with the prefrontal cortex in ASD individuals, after controlling for age. Recently, Nomi and Uddin (2015) observed both hypo-connectivity and hyper-connectivity in ASD children for within-network connections, but hypo-connectivity in non-ASD children, adolescents, and adults. It is also observed that connectivity (both short- and long-range) within functional networks is reduced, whereas internetwork connectivity is enhanced in children and adolescents with ASD (Rudie et al., 2013; Supekar et al. 2013). These studies emphasized the complexity of the network organization in ASD, and they warrant future study in revealing which factors are responsible for the aberrant connections in ASDs.

Attention deficit/hyperactivity disorder

ADHD is one of the most prevalent developmental disorders, characterized by inattention, hyperactivity, and impulsivity. Like ASD, ADHD patients also show aberrant connectivity in some networks. For example, the DMN shows atypical development in ADHD patients. It is believed that delayed maturation of the DMN and its connections to the fronto-parietal and attention networks may underlie the pathology of ADHD (De La Fuente et al., 2013; Sripada et al., 2014a,b). Other scholars have reported that alterations in the frontal-temporal-occipital and fronto-amygdala-occipital networks are closely related to inattention and hyperactivity in young adults with ADHD (Cocchi et al., 2012).

Reduced functional connectivity in ADHD is often observed in the DMN and the cortico-striatum network (Liston et al., 2011; Posner et al., 2014a,b). In the DMN, there is decreased connectivity between the PCC/precuneus and ACC or the nearby frontal cortex (Castellanos et al., 2008; Fair et al., 2010; Sripada et al., 2014a,b), and between the DMN and the VAN (Sripada et al., 2014a,b). Compared with normal controls, the negative correlation between the dorsal ACC (dACC) and the DMN is lower in ADHD boys (Sun et al., 2012). The negative correlation between the DMN and the cognitive control network is either diminished or absent in ADHD patients (Posner et al., 2014a,b). In the cortico-striatum network, reduced connections were observed between the caudate and the superior and middle frontal gyri (SFG/MFG) (Hong et al., 2015), between the putamen and the para-hippocampus (Hong et al., 2015), and between the left putamen and the right frontal and limbic regions and the DMN (Cao et al., 2009). In addition, Tomasi and Volkow (2012) reported lowered connectivity between the orbital frontal cortex (OFC) and the superior parietal lobe (SPL).

On the other hand, increased connectivity in ADHD was reported for the visual cortex and para-hippocampus (Cao et al., 2006). Increased connectivity between the OFC and the ACC and between the OFC and the ventral striatum may highlight an impaired interaction between the control and reward pathways in producing attention and motivation deficits in ADHD (Tomasi and Volkow, 2012). Increased connectivity is also observed between the dACC, the thalamus, the cerebellum, the insula, and the pons (Tian et al., 2006). Moreover, there is reduced connectivity between the salience network and sensorimotor

network and between the anterior DMN and the posterior DMN (Choi et al., 2013).

Furthermore, some atypical network characteristics were reported in ADHD. For example, children with ADHD showed higher local efficiency and local clustering and lower global efficiency (Cao et al., 2014a,b). Decreased nodal efficiency was observed in the OFC and several temporal and occipital regions, whereas increased nodal efficiency was found in the inferior frontal gyrus (Wang et al., 2009). Tomasi and Volkow (2012) found lower connectivity in the SPL, the precuneus, and the cerebellum but higher short-range connectivity in the ventral striatum and the OFC (the reward-motivation system). Barber et al. (2015) observed better attention in ADHD when the anti-correlation of the cingulo-opercular network with DMN is higher; but this relationship is reversed for the TD controls. Lately, Sripada et al. (2014a,b) observed a developmental lag in ADHD children in the connectivity between the dorsal medial prefrontal cortex (PFC) and the PCC, within the DMN, and between the DMN and the right PFC and anterior insula. Because ADHD patients move more frequently, they are more vulnerable to motion artifacts, and may result in increased short-range connections compared to long-range connections. Such an issue is addressed in recent studies.

Mood disorders

Anxiety, depression, and bipolar disorders are common mental disorders in children. In these disorders, emotional networks are often disturbed. Specifically, reduced connectivity is reported (1) between the subgenual ACC (sgACC, a sub-region of the ACC engaged in the processing of emotional information) and the dACC, several frontal and temporal regions in children with major depressive disorders (MDD) (Gaffrey et al., 2010); (2) between the amygdala and the DMN in MDD children (Hulvershorn et al., 2011); (3) between the sgACC and the precuneus in MDD adolescents (Connolly et al., 2013); (4) between the amygdala and the hippocampus, the para-hippocampus, and the brainstem in MDD adolescents (Cullen et al., 2014); (5) between the PCC and the middle temporal gyrus (MTG), the inferior parietal lobule, and the cerebellum in depressed preschoolers (Gaffrey et al., 2012); (6) between the amygdala and the cortical regulation networks in depressive children (Luking et al., 2011); (7) between the amygdala and the prefrontal cortex in anxious adolescents (Burghy et al., 2012); (8) within the task-positive network in depressive and anxious children (Sylvester et al., 2013); and (9) between the DLPFC and the STG in children with bipolar disorders (Dickstein et al., 2010).

Moreover, enhanced connectivity is also observed. In anxious children, connectivity is enhanced (1) between the amygdala and the brain regions involved in emotion and attention (Qin et al., 2014); (2) between the DMN and the insula (Dennis et al., 2011); and (3) between the amygdala, the insula, and the STG (Roy et al., 2013). In children with MDD, enhanced connectivity is observed (1) between the amygdala and the limbic system (Luking et al., 2011); (2) between the sgACC and the precuneus (Gaffrey et al., 2010); and (3) within the regions of the striatum (Phillips et al., 2003). In depressed preschoolers, connectivity between the PCC and the subgenual and anterior cingulate cortices, and the anterior MTG bilaterally was increased (Gaffrey et al., 2012). In children with bipolar disorders, connectivity within the dACC and affective, executive, and sensorimotor networks was enhanced (Wu et al., 2013).

Brain plasticity, experience and functional networks

Neuronal plasticity refers to the structural or functional changes of the brain in response to changes in the internal or external environments (May, 2011; Cai et al., 2014). According to the Hebbian theory (Hebb, 1949), neurons with a history of simultaneous activations tend to produce stronger associations with each other. This is also true at the network level (Sporns, 2013). Thus, we can improve our cognitive abilities by modulating brain networks via training and interventions (Taya et al., 2015). In the domain of neuroplasticity and training, there are some complex questions which need to be clarified.

The transfer effect is a core issue of learning. The transfer effect consists of near transfer and far transfer. The near transfer refers to an improvement in tasks that are similar to the trained task, whereas the far transfer is an improvement in tasks that are significantly different from the trained task (Kirk et al., 2015). It is suggested that the transfer effect can be enhanced if we train modality-independent higher-level executive control processes rather than basic processes or specific strategies (Lustig et al., 2009). Researchers have proposed that the transfer effects take place only if the tasks in training and transfer share similar cognitive processing or brain networks (Karbach and Schubert, 2013). It is still an open question concerning what kind of learning most efficiently improves the occurrence of transfer effects (Karbach and Schubert, 2013).

The manifestations of neuronal plasticity in physical or cognitive training are observed from childhood to

older adulthood (May, 2011) and from healthy individuals to patients (Karbach and Schubert, 2013; Chan et al., 2015a,b). However, the way to measure training effects varies across studies (Grady and Garrett, 2014). It is still not yet completely understood why learners benefit more than others from particular interventions. This question is especially important for selecting effective training paradigms for people with specific needs (Karbach and Schubert, 2013).

A child's brain has the highest plasticity, whereas the maturation curve has an inverted U-shape (Figure 2) (Wass et al., 2012; Cao et al., 2014a,b; Guerra-Carrillo et al., 2014). This suggests that the plasticity and maturation may not necessarily share the same processes. For instance, the fronto-parietal network is associated with working memory maturation, whereas the caudate and thalamus parts of the striatum are related to its plasticity (Klingberg, 2014). Similarly, plasticity in children's and adults' brains may occur via different mechanisms (Maguire et al., 2006).

Training restores functional networks

The brain is a complex system consisting of hierarchical networks. Bressler and Menon (2010) suggested that cognitive functions are supported by the interactions of distributed areas in brain networks. Hence, the brain network perspective provides valuable insights into human development and training. For example, physical or cognitive training, although focusing on a single brain region, can affect other brain regions via functional connectivity; the training effects differ between the network nodes, depending on their status in the network (e.g. hubs vs. non-hubs); training can change the cost of information transfer across the regions in a network (Taya et al., 2015).

For basic skill training, motor skill learning is a widely studied domain. The effectiveness of motor learning in children depends on the way and time of learning (Chan et al., 2015a,b; Ren et al., 2015). Compared to adults, children take longer time for the automatization of motor skill, and the extent of automatization is lower in children (Ruitenberg et al., 2013). It was observed that similar to adults, children's implicit motor learning was associated with subcortical activity but to a less extent (Thomas et al., 2004). This demonstrated that the implicit motor learning system is still undergoing development during childhood. Neuroimaging results of motor learning in children are still lacking and require further exploration in the future.
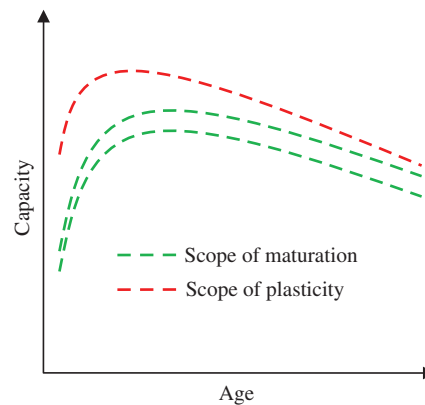

Figure 2: Plasticity provides rooms for capacity augmentation in addition to maturation-related gains.

In adults, even a short session (11 min) of visuomotor practice can modulate the connectivity of the fronto-parietal and the cerebellar networks (Albert et al., 2009). Local efficiency is also increased after motor learning, thereby indicating an increase in local information transfer (Sami and Miall, 2013). Motor skill learning can be divided into a fast stage and a slow stage (Dayan and Cohen, 2011). In the fast stage, remarkable gains occur in a single training session. In the slow stage, further improvements are slowly achieved across several sessions of training. Significant activation enhancement can be seen in a relative posterior network in the fast stage, such as the posterior cerebellum, the dorsomedial striatum, the supplementary motor area (SMA), the PM, and the PCC. In contrast, reduced activation can be found in a relative anterior network, such as the preSMA, the primary motor cortex (M1), and the DLPFC. In the slow stage, activation increases in the cortico-striatum network including the primary somatosensory cortex (S1), the M1, the SMA, and the dorsolateral striatum, whereas reduced activation can be seen in the lateral cerebellum (Dayan and Cohen, 2011). In learning a finger sequence over a 4-week period, it was found that during the first 2 weeks of training, the connectivity between the right postcentral gyrus and the right supramarginal gyri increased, along with behavioral performance improvement. In the second 2 weeks, the connectivity between these regions decreased, while behavioral performance maintained unchanged (Ma et al., 2011). Moreover, offline consolidation of motor sequence learning is related to greater interactions within the cortico-striatal system (Debas et al., 2014).

Juggling training for 6 weeks improved performance in both the high-intensity (30 min per day) and the low-intensity (15 min per day) groups similarly. However, the low-intensity group demonstrated an increase in connectivity

in the motor network, whereas the high-intensity group had a decrease in connectivity (Sampaio-Baptista et al., 2015). This shows that training intensity can modulate training-related changes in functional connectivity. Nature of practice is also an important modulator. Different temporal patterns of connectivity change were observed after learning a procedural skill in groups practicing explicitly and implicitly. In the explicit group, connectivity between the frontal, the cerebellar, and the visual areas increased immediately after skill acquisition. Connectivity between the cerebellum, the thalamus, and the basal ganglia was strengthened 30 min later. After 6 h, enhanced sensorimotor network connectivity can be observed. Implicit learners, however, showed increased connectivity between the precentral and the sensorimotor areas immediately after practice. After 30 min, a strengthened cerebello-thalamo-basal ganglionic network was detected, similar to that observed in the explicit group. After 6 h, connectivity increased in the MTL and decreased in the precentral and the sensorimotor areas (Sami et al., 2014). In addition to physical practice, motor imagery training can also influence resting-state functional networks. Two weeks of motor imagery practice can strengthen the connectivity between the sensorimotor and the visual networks and reduce connectivity in the DMN (Zhang et al., 2014).

In the domain of higher cognition, working memory and attention training are two of the most intensively studied domains. Training in these fields has shown a consistent near transfer effect but a dubious far transfer effect (Klingberg et al., 2002; Tamm et al., 2013). It is obvious that both training strategies and training approaches will impact training effects. Cognitive overload, mental fatigue, training intensity, and duration are important factors that influence the effects of training interventions (Kirk et al., 2015; Taya et al., 2015). For example, Alloway et al. (2013) demonstrated that high-frequency working memory training is more beneficial than low-frequency training. So far, brain stimulation (e.g. steady-state stimulation, transcranial magnetic stimulation, and transcranial direct current stimulation; Thut et al., 2011; Wang et al., 2014a,b) and psychopharmacology (Repantis et al., 2010; Taya et al., 2015) are the principal approaches in physical and cognitive training. The improvement of training approaches and learning strategies is of importance for resolving the key issues of skill learning in future studies, such as the transfer effect and the persistence of training effects in different populations.

Complex cognitive training in older adults can bring about greater connectivity in the DMN and the CEN (Chapman et al., 2015). Jolles et al. (2013) reported increased functional connectivity within the fronto-parietal network and reduced connectivity between the MPFC and the right posterior MTG after working memory training in young adults, and such effects were not observed in 12-year-olds, thereby suggesting that working memory training-related changes in functional connectivity are age dependent. It is also observed that working memory training increased the within-network connectivity in the DMN and the attention network, while it decreased the connectivity between these networks (Takeuchi et al., 2013). In the domain of attention, experienced mediators showed weaker functional connectivity between the DMN regions for self-referential processing and emotional appraisal and greater connectivity between the dorsal MPFC and the right IPL, compared to beginner mediators (Taylor et al., 2013).

Distinct training effects in different stages can also be seen in training about complex cognitions. For instance, after extended musical training, the prefrontal cortex is more engaged while performing finger tapping along with the rhythms (Chen et al., 2008), and the interaction between the auditory and premotor cortices is also increased when listening to a strong beat (Grahn and Rowe, 2009) in musicians than in non-musicians. The local functional connectivity in the salience network is greater in musicians than in non-musicians (Luo et al., 2014). Connectivity between perceptual and motor networks is strengthened in musicians (Luo et al., 2012). In the late training period, neural networks would differentiate between different kinds of musician. For example, when adjusting to pitch-shifted feedback, the auditory and motor cortices are engaged in singers (Zarate and Zatorre, 2008), whereas the auditory cortex and cerebellum are engaged in pianists (Pfordresher et al., 2014). After reading training, children with reading difficulties showed greater functional connectivity in the cingulo-opercular network than typical readers, which may demonstrate that the dyslexic children have greater gains with training (Horowitz-Kraus et al., 2015).

Implications and future research

We are still in the initial stages of understanding brain function at the system level. Although great progress has been made in revealing childhood development, aging processes, and the neuro-developmental mechanism of most mental disorders, how to avoid and rectify atypical development warrants further study. The perspective of brain network development would provide valuable insights into our understanding of childhood development because the development and maturation of brain

networks parallel the emergence and development of corresponding cognitive and motor functions (Byrge et al., 2014; Rothbart and Posner, 2015). The knowledge of brain network development will also facilitate skill learning studies by expounding how physical and cognitive training change the network characteristics.

The preservation and transfer effect of the gains in learning are key issues in future studies. Although much is known about learning effects on brain structure and function, the training effect is usually sustained for a relatively short period of time (May, 2011). How to prolong the effect of training is of clinical importance. Although some training programs can produce significant near transfer, far transfer is not consistently observed after training of higher cognition. Understanding how we can get stable near and far transfer in training is essential for improving the effectiveness of training programs. The developmental rules of brain networks may shed light on these questions.

Conclusions

An important issue in childhood development is the development of functional brain networks. We reviewed the typical and atypical developments of functional networks and summarized the theoretical relevance of network development. After that, we discussed the role of plasticity in network development and showed the implication of cognitive training in improving the function of brain networks. Considerable studies have provided strong evidence that brain network development is an essential mechanism during childhood development. Plasticity-based learning is an important means by which to promote typical network development and to rectify atypical network development.

References

Abrams, D.A., Lynch, C.J., Cheng, K.M., Phillips, J., Supekar, K., Ryali, S., Uddin, L.Q., and Menon, V. (2013). Underconnectivity between voice-selective cortex and reward circuitry in children with autism. Proc. Natl. Acad. Sci. U. S. A. *110*, 12060–12065.

Alaerts, K., Woolley, D.G., Steyaert, J., Di Martino, A., Swinnen, S.P., and Wendoerth, N. (2014). Underconnectivity of the superior temporal sulcus predicts emotion recognition deficits in autism. Soc. Cogn. Affect. Neurosci. *9*, 1589–1600.

Albert, N.B., Robertson, E.M., and Miall, R.S. (2009). The resting human brain and motor learning. Curr. Biol. *19*, 1023–1027.

Alcauter, S., Lin, W., Smith, J.K., Short, S.J., Goldman, B.D., Reznick, J.S., Gilmore, J.H., and Gao, W. (2014). Development of thalamocortical connectivity during infancy and its cognitive correlations. J. Neurosci. *34*, 9067–9075.

Alloway, T.P., Bibile, V., and Lau, G. (2013). Computerized working memory training: can it lead to gains in cognitive skills in students? Comput. Hum. Behav. *29*, 632–638.

Anderson, J.S., Druzgal, T.J., Froehlich, A., DuBray, M.B., Lange, N., Alexander, A.L., Abildskov, T., Nielsen, J.A., Cariello, A.N., et al. (2011). Decreased interhemispheric functional connectivity in autism. Cereb. Cortex *21*, 1134–1146.

Assaf, M., Jagannathan, K., Calhoun, V.D., Miller, L., Stevens, M.C., Sahl, R., O'Boyle, J.G., Schultz, R.T., and Pearlson, G.D. (2010). Abnormal functional connectivity of default mode sub-networks in autism spectrum disorder patients. Neuroimage *53*, 247–256.

Barber, A.D., Caffo, B.S., Pekar, J.J., and Mostofsky, S.H. (2013). Developmental changes in within- and between-network connectivity between late childhood and adulthood. Neuropsychologia *51*, 156–167.

Barber, A.D., Jacobson, L.A., L.Wexler, J., Nebel, M.B., Caffo, B.S., Pekar, J.J., and Mostofsky, S.H. (2015). Connectivity supporting attention in children with attention deficit hyperactivity disorder. Neuroimage Clin. *7*, 68–81.

Bos, D.J., van Raalten, T.R., Oranje, B., Smits, A.R., Kobussen, N.A., van Belle, J., Rombouts, S.A.R.B., and Durston, S. (2014). Developmental differences in higher-order resting-state networks in autism spectrum disorder. Neuroimage Clin. *4*, 820–827.

Bressler, S.L. and Menon, V. (2010). Large-scale brain networks in cognition: emerging methods and principles. Trends Cogn. Sci. *14*, 277–290.

Burghy, C.A., Stodola, D.E., Ruttle, P.L., Molloy, E.K., Armstrong, J.M., Oler, J.A., Fox, M.E., Hayes, A.S., Kalin, N.H., Essex, M.J., et al. (2012). Developmental pathways to amygdala-prefrontal function and internalizing symptoms in adolescence. Nat. Neurosci. *15*, 1736–1741.

Byrge, L., Sporns, O., and Smith, L.B. (2014). Developmental process emerges from extended brain-body-behavior networks. Trends Cogn. Sci., *18*, 395–403.

Cai, L., Chan, J.S.Y., Yan, J.H., and Peng, K. (2014). Brain plasticity and motor practice in cognitive aging. Front. Aging Neurosci. *6*, 31.

Cao, M., Shu, N., Cao, Q., Wang, Y., and He, Y. (2014a). Imaging functional and structural brain connectomics in attention-deficit/hyperactivity disorder. Mol. Neurobiol. *50*, 1111–1123.

Cao, M., Wang, J.-H., Dai, Z.-J., Cao, X.-Y., Jiang, L.-L., Fan, F.-M., Song, X.-W., Xia, M.-R., Shu, Ni, Dong, Q., et al. (2014b). Topological organization of the human brain functional connectome across the lifespan. Dev. Cogn. Neurosci. *7*, 76–93.

Cao, Q., Zang, Y., Sun, L., Sui, M., Long, X., Zou, Q., and Wang, Y. (2006). Abnormal neural activity in children with attention deficit hyperactivity disorder: a resting-state functional magnetic resonance imaging study. Neuroreport *17*, 1033–1036.

Cao, X., Cao, Q., Long, X., Sun, L., Sui, M., Zhu, C., Zuo, X., Zang, Y., and Wang, Y. (2009). Abnormal resting-state functional connectivity patterns of the putamen in medication-naïve children with attention deficit hyperactivity disorder. Brain Res. *1303*, 195–206.

Casey, B.J., Giedd, J.N., and Thomas, K.M. (2000). Structural and functional brain development and its relation to cognitive development. Biol. Psychol. *54*(1–3), 241–257.

Castellanos, F.X., Margulies, D.S., Kelly, C., Uddin, L.Q., Ghaffari, M., Kirsch, A., Shaw, D., Shehzad, Z., Di Martino, A., Biswal, B., et al. (2008). Cingulate-precuneus interactions: a new locus of dysfunction in adult attention-deficit/hyperactivity disorder. Biol. Psychiat. 63, 332–337.

Chai, X.J., Ofen, N., Gabrieli, J.D., and Whitfield-Gabrieli, S. (2014). Selective development of anticorrelated networks in the intrinsic functional organization of the human brain. J. Cognitive Neurosci. 26, 501–513.

Chan, J.S.Y., Luo, Y.J., Yan, J.H., Cai, L.Y., and Peng, K.P. (2015a). Children's age modulates the effect of part and whole practice in motor learning. Hum. Movement Sci. 42, 261–272.

Chan, J.S.Y., Wu, Q., Liang, D., and Yan, J.H. (2015b). Visuospatial working memory training facilitates visually-aided explicit sequence learning. Acta Psychol. 161, 145–153.

Chapman, S.B., Aslan, S., Spence, J.S., Hart, J.J., Bartz, E.K., Didehbani, N., Keebler, M.W., Gardner, C.M., Strain, J.F., DeFina, L.F., et al. (2015). Neural mechanisms of brain plasticity with complex cognitive training in healthy seniors. Cereb. Cortex 25, 396–405.

Chen, J.L., Penhune, V.B., and Zatorre, R.J. (2008). Moving on time: brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. J. Cognitive Neurosci. 20, 226–239.

Choi, J., Jeong, B., Lee, S.W., and Go, H. (2013). Aberrant development of functional connectivity among resting state-related functional networks in medication-naive ADHD children. PLoS One 8, e83516.

Cocchi, L., Bramati, I.E., Zalesky, A., Furukawa, E., Fontenelle, L.F., Moll, J., Tripp, G., and Mattos, P. (2012). Altered functional brain connectivity in a non-clinical sample of young adults with attention-deficit/hyperactivity disorder. J. Neurosci. 32, 17753–17761.

Connolly, C.G., Wu, J., Ho, T.C., Hoeft, F., Wolkowitz, O., Eisendrath, S., Frank, G., Hendren, R., Max, J.E., Paulus, M.P., et al. (2013). Resting-state functional connectivity of subgenual anterior cingulate cortex in depressed adolescents. Biol. Psychiat. 74, 898–907.

Cullen, K.R., Westlund, M.K., Klimes-Dougan, B., Mueller, B.A., Houri, A., Eberly, L.E., and Lim, K.O. (2014). Abnormal amygdala resting-state functional connectivity in adolescent depression. JAMA Psychiatry 71, 1138–1147.

Damaraju, E., Caprihan, A., Lowe, J., Allen, E., Calhoun, V., and Phillips, J. (2014). Functional connectivity in the developing brain: a longitudinal study from 4 to 9 months of age. Neuroimage 84, 169–180.

Dayan, E. and Cohen, L.G. (2011). Neuroplasticity subserving motor skill learning. Neuron 72, 443–454.

de Bie, H.M.A., Boersma, M., Adriaanse, S., Veltman, D.J., Wink, A.M., Roosendaal, S.D., Barkhof, F., Stam, C.J., Oostrom, K.J., Delemarre-van de Waal, H.A., et al. (2010). Resting-state networks in awake five- to eight-year old children. Hum. Brain Mapp. 33, 1189–1201.

De La Fuente, A., Xia, S., Branch, C., and Li, X. (2013). A review of attention-deficit/hyperactivity disorder from the perspective of brain networks. Front. Hum. Neurosci. 7, 192.

Debas, K., Carrier, J., Barakat, M., Marrelec, G., Bellec, P., Tahar, A.H., Karni, A., Ungerleider, L.G., Benali, H., and Doyon, J. (2014). Off-line consolidation of motor sequence learning results in greater integration within a cortico-striatal functional network. Neuroimage 99, 50–58.

Dennis, E.L., Gotlib, I.H., Thompson, P.M., and Thomason, M.E. (2011). Anxiety modulates insula recruitment in resting-state functional magnetic resonance imaging in youth and adults. Brain Connect. 1, 245–254.

Di Martino, A., Kelly, C., Grzadzinski, R., Zuo, X.N., Mennes, M., Mairena, M.A., Lord, C., Castellanos, F.X., and Milham, M.P. (2011). Aberrant striatal functional connectivity in children with autism. Biol. Psychiat. 69, 847–856.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. Child Dev. 71, 44–56.

Dickstein, D.P., Gorrostieta, C., Ombao, H., Goldberg, L.D., Brazel, A.C., Gable, C.J., Kelly, C., Gee, D.G., Zuo, X.-N., Castellanos, F.X., et al. (2010). Fronto-temporal spontaneous resting state functional connectivity in pediatric bipolar disorder. Biol. Psychiat. 68, 839–846.

Doria, V., Beckmann, C.F., Arichi, T., Merchant, N., Groppo, M., Turkheimer, F.E., Counsell, S.J., Murgasova, M., Aljabar, P., Nunes, R.G., et al. (2010). Emergence of resting state networks in the preterm human brain. Proc. Natl. Acad. Sci. U. S. A. 107, 20015–20020.

Dosenbach, N.U., Nardos, B., Cohen, A.L., Fair, D.A., Power, J.D., Church, J.A., Nelson, S.M., Wig, G.S., Vogel, A.C., Lessov-Schlaggar, C.N., et al. (2010). Prediction of individual brain maturity using fMRI. Science 329 (5997), 1358–1361.

Durston, S., Davidson, M.C., Tottenham, N., Galvan, A., Spicer, J., Fossella, J.A., and Casey, B.J. (2006). A shift from diffuse to focal cortical activity with development. Dev. Sci. 9, 1–8.

Ebisch, S.J., Gallese, V., Willems, R.M., Mantini, D., Groen, W.B., Romani, G.L., Buitelaar, J.K., and Bekkering, H. (2011). Altered intrinsic functional connectivity of anterior and posterior insula regions in high-functioning participants with autism spectrum disorder. Hum. Brain Mapp. 32, 1013–1028.

Ernst, M., Torrisi, S., Balderston, N., Grillon, C., and Hale, E.A. (2015). fMRI functional connectivity applied to adolescent neurodevelopment. Annu. Rev. Clin. Psychol. 11, 361–377.

Fair, D.A., Dosenbach, N.U., Church, J.A., Cohen, A.L., Brahmbhatt, S., Miezin, F.M., Barch, D.M., Raichle, M.E., Petersen, S.E., and Schlaggar, B.L. (2007). Development of distinct control networks through segregation and integration. Proc. Natl. Acad. Sci. U. S. A. 104, 13507–13512.

Fair, D.A., Cohen, A.L., Dosenbach, N.U., Church, J.A., Miezin, F.M., Barch, D.M., Raichle, M.E., Petersen, S.E., and Schlaggar, B.L. (2008). The maturing architecture of the brain's default network. Proc. Natl. Acad. Sci. U. S. A. 105, 4028–4032.

Fair, D.A., Cohen, A.L., Power, J.D., Dosenbach, N.U.F., Church, J.A., Miezin, F.M., Schlaggar, B.L., and Petersen, S.E. (2009). Functional brain networks develop from a "local to distributed" organization. PLoS Comput. Biol. 5, e1000381.

Fair, D., Posner, J., Nagel, B., Bathula, D., Dias, T., Mills, K., Blythe, M.S., Giwa, A., Schmitt, C.F., and Nigg, J. (2010). Atypical default network connectivity in youth with attention-deficit/hyperactivity disorder. Biol. Psychiat. 68, 1084–1091.

Farrant, K. and Uddin, L.Q. (2015). Asymmetric development of dorsal and ventral attention networks in the human brain. Dev. Cogn. Neurosci. 12, 165–174.

Fjell, A.M., Walhovd, K.B., Brown, T.T., Kuperman, J.M., Chung, Y., Hagler, D.J., Venkatraman, V., Roddey, J.C., Erhart, M., McCabe, C., et al. (2012). Multimodal imaging of the self-regulating developing brain. Proc. Natl. Acad. Sci. U. S. A. 109, 19620–19625.

Fornito, A., Zalesky, A., and Breakspear, M. (2015). The connectomics of brain disorders. Nat. Rev. Neurosci. *16*, 150–172.

Fox, M.D., and Raichle, M.E. (2007). Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nat. Rev. Neurosci. *8*, 700–711.

Fransson, P., Skiöld, B., Horsch, S., Nordell, A., Blennow, M., Lagercrantz, H., and Åden, U. (2007). Resting-state networks in the infant brain. Proc. Natl. Acad. Sci. U. S. A. *104*, 15531–15536.

Fransson, P., Aden, U., Blennow, M., and Lagercrantz, H. (2011). The functional architecture of the infant brain as revealed by resting-state fMRI. Cereb. Cortex *21*, 145–154.

Gabard-Durnam, L.J., Flannery, J., Goff, B., Gee, D.G., Humphreys, K.H., Telzer, E., Hare, T., and Tottenham, N. (2014). The development of human amygdala functional connectivity at rest from 4 to 23 years: a cross-sectional study. Neuroimage *95*, 193–207.

Gaffrey, M.S., Luby, J.L., Repovs, G., Belden, A.C., Botteron, K.N., Luking, K.R., and Barch, D.M. (2010). Subgenual cingulate connectivity in children with a history of preschool-depression. Neuroreport *21*, 1182–1188.

Gaffrey, M.S., Luby, J.L., Botteron, K., Repovs, G., and Barch, D.M. (2012). Default mode network connectivity in children with a history of preschool onset depression. J. Child Psychol. Psychiatry *53*, 964–972.

Gao, W., Zhu, H., Giovanello, K.S., Smith, J.K., Shen, D., Gilmore, J.H., and Lin, W. (2009). Evidence on the emergence of the brain's default network from 2-week-old to 2-year-old healthy pediatric subjects. Proc. Natl. Acad. Sci. U. S. A. *106*, 6790–6795.

Gao, W., Gilmore, J.H., Shen, D., Smith, J.K., Zhu, H., and Lin, W. (2013). The synchronization within and interaction between the default and dorsal attention networks in early infancy. Cereb. Cortex *23*, 594–603.

Gao, W., Alcauter, S., Elton, A., Hernandez-Castillo, C.R., Smith, J.K., Ramirez, J., and Lin, W.L. (2015a). Functional network development during the first year: relative sequence and socioeconomic correlations. Cereb. Cortex *25*, 2919–2928.

Gao, W., Alcauter, S., Smith, J.K., Gilmore, J.H., and Lin, W. (2015b). Development of human brain cortical network architecture during infancy. Brain Struct. Funct. *220*, 1173–1186.

Gohel, S.R., and Biswal, B.B. (2015). Functional integration between brain regions at rest occurs in multiple-frequency bands. Brain Connect. *5*, 23–34.

Grady, C.L., and Garrett, D.D. (2014). Understanding variability in the BOLD signal and why it matters for aging. Brain Imaging Behav. *8*, 274–283.

Grahn, J.A., and Rowe, J.B. (2009). Feeling the beat: premotor and striatal interactions in musicians and nonmusicians during beat perception. J. Neurosci. *29*, 7540–7548.

Guerra-Carrillo, B., Mackey, A.P., and Bunge, S.A. (2014). Resting-state fMRI A window into human brain plasticity. Neuroscientist *20*, 522–533.

Hebb, D.O. (1949). The Organization of Behavior: A Neuropsychological Approach (New York: John Wiley & Sons).

Hernandez, L.M., Rudie, J.D., Green, S.A., Bookheimer, S., and Dapretto, M. (2015). Neural signatures of autism spectrum disorders: insights into brain network dynamics. Neuropsychopharmacology, *40*, 171–189.

Hoff, G.E.A., Van den Heuvel, M.P., Benders, M.J.N.L., Kersbergen, K.J., and De Vries, L.S. (2013). On development of functional brain connectivity in the young brain. Front. Hum. Neurosci. *7*, 650.

Hong, S.-B., Harrison, B.J., Fornito, A., Sohn, C.-H., Song, I.-C., and Kim, J.-W. (2015). Functional dysconnectivity of corticostriatal circuitry and differential response to methylphenidate in youth with attention-deficit/hyperactivity disorder. J. Psychiatry Neurosci. *40*, 46–57.

Horowitz-Kraus, T., Toro-Serey, C., and DiFrancesco, M. (2015). Increased resting-state functional connectivity in the cingulo-opercular cognitive-control network after intervention in children with reading difficulties. PLoS One *10*, e0133762.

Hulvershorn, L.A., Cullen, K., and Anand, A. (2011). Toward dysfunctional connectivity: a review of neuroimaging findings in pediatric major depressive disorder. Brain Imaging Behav. *5*, 307–328.

Hulvershorn, L.A., Cullen, K.R., Francis, M.M., and Westlund, M.K. (2014). Developmental resting state functional connectivity for clinicians. Curr. Behav. Neurosci. Rep. *1*, 161–169.

Hwang, K., Hallquist, M., and Luna, B. (2013). The development of hub architecture in the human functional brain network. Cereb. Cortex *23*, 2380–2393.

Johnson, M.H. (2001). Functional brain development in humans. Nat. Rev. Neurosci. *2*, 475–483.

Johnson, M.H. (2011). Interactive specialization: a domain-general framework for human functional brain development? Dev. Cogn. Neurosci. *1*, 7–21.

Jolles, D.D. and Crone, E.A. (2012). Training the developing brain: a neurocognitive perspective. Front. Hum. Neurosci. *6*, 76.

Jolles, D.D., van Buchem, M.A., Crone, E.A., and Rombouts, S.A.R.B. (2011). A comprehensive study of whole-brain functional connectivity in children and young adults. Cereb. Cortex *21*, 385–391.

Jolles, D.D., van Buchem, M.A., Crone, E.A., and Rombouts, S.A.R.B. (2013). Functional brain connectivity at rest changes after working memory training. Hum. Brain Mapp. *34*, 396–406.

Karbach, J. and Schubert, T. (2013). Training-induced cognitive and neural plasticity. Front. Hum. Neurosci. *7*, 48.

Karmiloff-Smith, A. (2009). Nativism versus neuroconstructivism: rethinking the study of developmental disorders. Dev. Psychol. *45*, 56–63.

Kelly, A.C., Di Martino, A., Uddin, L.Q., Shehzad, Z., Gee, D.G., Reiss, P.T., Margulies, D.S., Castellanos, F.X., and Milham, M.P. (2009). Development of anterior cingulate functional connectivity from late childhood to early adulthood. Cereb. Cortex *19*, 640–657.

Kirk, H.E., Gray, K., Riby, D.M., and Cornish, K.M. (2015). Cognitive training as a resolution for early executive function difficulties in children with intellectual disabilities. Res. Dev. Disabil. *38*, 145–160.

Klingberg, T. (2014). Childhood cognitive development as a skill. Trends Cogn. Sci. *18*, 573–579.

Klingberg, T., Forssberg, H., and Westerberg, H. (2002). Training of working memory in children with ADHD. J. Clin. Exp, Neuropsychol. *24*, 781–791.

Lin, W., Zhu, Q., Gao, W., Chen, Y., Toh, C.-H., Styner, M., Gerig, G., Smith, J.K., Biswal, B., and Gilmore, J. (2008). Functional connectivity MR imaging reveals cortical functional connectivity in the developing brain. Am. J. Neuroradiol. *29*, 1883–1889.

Liston, C., Cohen, M.M., Teslovich, T., Levenson, D., and Casey, B.J. (2011). Atypical prefrontal connectivity in attention-deficit/hyperactivity disorder: pathway to disease or pathological end point? Biol. Psychiat. *69*, 1168–1177.

Liu, W.-C., Flax, J.F., Guise, K.G., Sukul, V., and Benasich, A.A. (2008). Functional connectivity of the sensorimotor area in naturally sleeping infants. Brain Res. *1223*, 42–49.

Luking, K.R., Repovs, G., Belden, A.C., Gaffrey, M.S., Botteron, K.N., Luby, J.L., and Barch, D.M. (2011). Functional connectivity of the amygdala in early-childhood-onset depression. J. Am. Acad. Child Adolesc. Psychiatry *50*, 1027–1041.

Luna, B. and Sweeney, J.A. (2004). The emergence of collaborative brain function: FMRI studies of the development of response inhibition. Ann. N. Y. Acad. Sci. *1021*, 296–309.

Luo, C., Guo, Z., Lai, Y., Liao, W., Liu, Q., Kendrick, K.M., Yao, D.-z., and Li, H. (2012). Musical training induces functional plasticity in perceptual and motor networks: insights from resting-state fMRI. PLoS One *7*, e36568.

Luo, C., Tu, S., Peng, Y., Gao, S., Li, J., Dong, L., Li, G., Lai, Y., Li, H., and Yao, D. (2014). Long-term effects of musical training and functional plasticity in salience system. Neural Plast. *2014*, 180138.

Lustig, C., Shah, P., Seidler, R., and Reuter-Lorenz, P.A. (2009). Aging, training, and the brain: a review and future directions. Neuropsychol. Rev. *19*, 504–522.

Lynch, C.J., Uddin, L.Q., Supekar, K., Khouzam, A., Phillips, J., and Menon, V. (2013). Default mode network in childhood autism: posteromedial cortex heterogeneity and relationship with social deficits. Biol. Psychiat. *74*, 212–219.

Ma, L., Narayana, S., Robin, D.A., Fox, P.T., and Xiong, J. (2011). Changes occur in resting state network of motor system during 4 weeks of motor skill learning. Neuroimage *58*, 226–233.

Maguire, E.A., Woollett, K., and Spiers, H.J. (2006). London taxi drivers and bus drivers: a structural MRI and neuropsychological analysis. Hippocampus *16*, 1091–1101.

May, A. (2011). Experience-dependent structural plasticity in the adult human brain. Trends Cogn. Sci. *15*, 475–482.

Menon, V. (2011). Large-scale brain networks and psychopathology: a unifying triple network model. Trends Cogn. Sci. *15*, 483–506.

Menon, V. (2013). Developmental pathways to functional brain networks: emerging principles. Trends Cogn. Sci. *17*, 627–640.

Monk, C.S., Peltier, S.J., Wiggins, J.L., Weng, S., Carrasco, M., Risi, S., and Lord, C. (2009). Abnormalities of intrinsic functional connectivity in autism spectrum disorders. Neuroimage *47*, 764–772.

Nair, A., Treiber, J.M., Shukla, D.K., Shih, P., and Muller, R. (2013). Impaired thalamocortical connectivity in autism spectrum disorder: a study of functional and anatomical connectivity. Brain *136*, 1942–1955.

Nomi, J.S. and Uddin, L.Q. (2015). Developmental changes in large-scale network connectivity in autism. Neuroimage Clin. *7*, 732–741.

Padmanabhan, A., Lynn, A., Foran, W., Luna, B., and O'Hearn, K. (2013). Age related changes in striatal resting state functional connectivity in autism. Front. Hum. Neurosci. *7*, 814.

Petersen, S.E. and Posner, M.I. (2012). The attention system of the human brain: 20 years after. Annu. Rev. Neurosci. *35*, 73–89.

Pfordresher, P.Q., Mantell, J.T., Brown, S., Zivadinov, R., and Cox, J.L. (2014). Brain responses to altered auditory feedback during musical keyboard production: an fMRI study. Brain Res. *1556*, 28–37.

Phillips, M.L., Drevets, W.C., Rauch, S.L., and Lane, R. (2003). Neurobiology of emotion perception I: the neural basis of normal emotion perception. Biol. Psychiat. *54*, 504–514.

Posner, J., Park, C., and Wang, Z. (2014a). Connecting the dots: a review of resting connectivity MRI studies in attention-deficit/hyperactivity disorder. Neuropsychol. Rev. *24*, 3–15.

Posner, M.I., Rothbart, M.K., Sheese, B.E., and Voelker, P. (2014b). Developing attention: behavioral and brain mechanisms. Adv. Neurosci. *2014*, 405094.

Power, J.D., Schlaggar, B.L., and Petersen, S.E. (2015). Recent progress and outstanding issues in motion correction in resting state fMRI. Neuroimage *105*, 536–551.

Qin, S., Young, C.B., Duan, X., Chen, T., Supekar, K., and Menon, V. (2014). Amygdala subregional structure and intrinsic functional connectivity predicts individual differences in anxiety during early childhood. Biol. Psychiat. *75*, 892–900.

Raz, A., and Buhle, J. (2006). Typologies of attentional networks. Nat. Rev. Neurosci. *7*, 367–379.

Redcay, E., Kennedy, D.P., and Courchesne, E. (2007). fMRI during natural sleep as a method to study brain function during early childhood. Neuroimage *38*, 696–707.

Ren, J., Guo, W., Yan, J.H., Liu, G.M., and Jia, F.J. (2015). Practice and nap schedules modulate children's motor learning. Dev. Psychobiol. *58*, 107–119.

Repantis, D., Schlattmann, P., Laisney, O., and Heuser, I. (2010). Modafinil and methylphenidate for neuroenhancement in healthy individuals: a systematic review. Pharmacol. Res. *62*, 187–206.

Rothbart, M.K., and Posner, M.I. (2015). The developing brain in a multitasking world. Dev. Rev. *35*, 42–63.

Rothbart, M.K., Sheese, B.E., Rueda, M.R., and Posner, M.I. (2011). Developing mechanisms of self-regulation in early life. Emot. Rev. *3*, 207–213.

Roy, A.K., Fudge, J.L., Kelly, C., Perry, J.S., Daniele, T., Carlisi, C., Benson, B., Castellanos, F.X., Milham, M.P., Pine, D.S., et al. (2013). Intrinsic functional connectivity of amygdala-based networks in adolescent generalized anxiety disorder. J. Am. Acad. Child Adolesc. Psychiatry *52*, 290–299. e292.

Rudie, J.D., Brown, J.A., Beck-Pancer, D., Hernandez, L.M., Dennis, E.L., Thompson, P.M., Bookheimer, S.Y., and Dapretto, M. (2013). Altered functional and structural brain network organization in autism. Neuroimage Clin. *2*, 79–94.

Rueda, M.R., Fan, J., McCandliss, B.D., Halparin, J.D., Gruber, D.B., Lercari, L.P., and Posner, M.I. (2004). Development of attentional networks in childhood. Neuropsychologia *42*, 1029–1040.

Ruitenberg, M.F.L., Abrahamse, E.L., and Verwey, W.B. (2013). Sequential motor skill in preadolescent children: the development of automaticity. J. Exp. Child Psychol. *115*, 607–623.

Sami, S., and Miall, R.C. (2013). Graph network analysis of immediate motor-learning induced changes in resting state BOLD. Front. Hum. Neurosci. *7*, 166.

Sami, S., Robertson, E.M., and Miall, R.C. (2014). The time course of task-specific memory consolidation effects in resting state networks. J. Neurosci. *34*, 3982–3992.

Sampaio-Baptista, C., Filippini, N., Stagg, C.J., Near, J., Scholz, J., and Johansen-Berg, H. (2015). Changes in functional connectivity and GABA levels with long-term motor learning. Neuroimage *106*, 15–20.

Sato, J.R., Salum, G.A., Gadelha, A., Picon, F.A., Pan, P.M., Viera, G., Zugman, A., Hoexter, M.Q., Anés, M., Moura, L.M., et al. (2014). Age effects on the default mode and control networks in typically developing children. J. Psychiat. Res. *58*, 89–95.

Sato, J.R., Salum, G.A., Gadelha, A., Viera, G., Zugman, A., Picon, F.A., Pan, P.M., Hoexter M.Q., Anés, M., Moura L.M., et al. (2015). Decreased centrality of subcortical regions during the transition to adolescence: a functional connectivity study. Neuroimage *104*, 44–51.

Seely, W.W., Menon, V., Schatzberg, A.F., Keller, J., Glover, G.H., Kenna, H., Reiss, A.L., and Greicius, M.D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. J. Neurosci. *27*, 2349–2356.

Sherman, L.E., Rudie, J.D., Pfeifer, J.H., Masten, C.L., McNealy, K., and Dapretto, M. (2014). Development of the default mode and central executive networks across early adolescence. Dev. Cogn. Neurosci. *10*, 148–159.

Smyser, C., Snyder, A., and Neil, J. (2011). Functional connectivity MRI in infants: exploration of the functional organization of the developing brain. Neuroimage *56*, 1437–1452.

Somerville, L.H., and Casey, B. (2010). Developmental neurobiology of cognitive control and motivational systems. Curr. Opin. Neurobiol. *20*, 1–6.

Sporns, O. (2013). Structure and function of complex brain networks. Dialogues Clin. Neurosci. *15*, 247–262.

Sripada, C.S., Kessler, D., and Angstadt, M. (2014a). Lag in maturation of the brain's intrinsic functional architecture in attention-deficit/hyperactivity disorder. Proc. Natl. Acad. Sci. U. S. A. *111*, 14259–14264.

Sripada, C., Kessler, D., Fang, Y., Welsh, R.C., Prem Kumar, K., and Angstadt, M. (2014b). Disrupted network architecture of the resting brain in attention-deficit/hyperactivity disorder. Hum. Brain Mapp. *35*, 4693–4705.

Stevens, M.C. (2009). The developmental cognitive neuroscience of functional connectivity. Brain Cogn. *70*, 1–12.

Sun, L., Cao, Q., Long, X., Sui, M., Cao, X., Zhu, C., Zuo, X., An, L., Song, Y., Zang, Y., et al. (2012). Abnormal functional connectivity between the anterior cingulate and the default mode network in drug-naïve boys with attention deficit hyperactivity disorder. Psychiatry Res. Neuroimaging, *201*, 120–127.

Supekar, K., Musen, M., and Menon, V. (2009). Development of large-scale functional brain networks in children. PLoS Biol. *7*, e1000157.

Supekar, K., Uddin, L.Q., Khouzam, A., Phillips, J., Gaillard, W.D., Kenworthy, L.E., Yerys, B.E., Vaidya, C.J., and Menon, V. (2013). Brain hyperconnectivity in children with autism and its links to social deficits. Cell Rep. *5*, 738–747.

Supekar, K., Uddin, L.Q., Prater, K., Amin, H., Greicius, M.D., and Menon, V. (2010). Development of functional and structural connectivity within the default mode network in young children. Neuroimage *52*, 290–301.

Sylvester, C.M., Barch, D.M., Corbetta, M., Power, J.D., Schlaggar, B.L., and Luby, J.L. (2013). Resting state functional connectivity of the ventral attention network in children with a history of depression or anxiety. J. Am. Acad. Child Adolesc. Psychiatry *52*, 1326–1336.

Takeuchi, H., Taki, Y., Nouchi, R., Hashizume, H., Sekiguchi, A., Kotozaki, Y., Nakagawa, S., Miyauchi, C.M., Sassa, Y., and Kawashima, R. (2013). Effects of working memory training on functional connectivity and cerebral blood flow during rest. Cortex *49*, 2106–2125.

Tamm, L., Epstein, J.N., Peugh, J.L., Nakonezny, P.A., and Hughes, C.W. (2013). Preliminary data suggesting the efficacy of attention training for school-aged children with ADHD. Dev. Cogn. Neurosci. *4*, 16–28.

Taya, F., Sun, Y., Babiloni, F., Thakor, N., and Bezerianos, A. (2015). Brain enhancement through cognitive training: a new insight from brain connectome. Front. Syst. Neurosci. *9*, 44.

Taylor, V.A., Daneault, V., Grant, J., Scavone, G., Breton, E., Roffe-Vidal, S., Courtemanche, J., Lavarenne, A.S., Marrelec, G., Benali, H., et al. (2013). Impact of meditation training on the default mode network during a restful state. Soc. Cogn. Affect. Neurosci. *8*, 4–14.

Thomas, K.M., Hunt, R.H., Vizueta, N., Sommer, T., Durston, S., Yang, Y.H., and Worden, M.S. (2004). Evidence of developmental differences in implicit sequence learning: an fMRI study of children and adults. J. Cognitive Neurosci. *16*, 1339–1351.

Thut, G., Schyns, P.G., and Gross, J. (2011). Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. Front. Psychol. *2*, 170.

Tian, L., Jiang, T., Wang, Y., Zang, Y., He, Y., Liang, M., Sui, M., Cao, Q., Hu, S., Peng, M., et al. (2006). Altered resting-state functional connectivity patterns of anterior cingulate cortex in adolescents with attention deficit hyperactivity disorder. Neurosci. Lett. *400*, 39–43.

Tomasi, D., and Volkow, N. (2012). Abnormal functional connectivity in children with attention-deficit/hyperactivity disorder. Biol. Psychiat. *71*, 443–450.

Uddin, L.Q., Supekar, K., and Menon, V. (2013). Reconceptualizing functional brain connectivity in autism from a developmental perspective. Front. Hum. Neurosci. *7*, 458.

Vogel, A.C., Power, J.D., Petersen, S.E., and Schlaggar, B.L. (2010). Development of the brain's functional network architecture. Neuropsychol. Rev. *20*, 362–375.

von dem Hagen, E., Stoyanova, R., Baron-Cohen, S., and Calder, A. (2013). Reduced functional connectivity within and between "social" resting state networks in autism spectrum conditions. Soc. Cogn. Affect. Neurosci. *8*, 694–701.

Wang, L., Zhu, C., He, Y., Zang, Y., Cao, Q., Zhang, H., Zhong, Q., and Wang, Y. (2009). Altered small-world brain functional networks in children with attention-deficit/hyperactivity disorder. Hum. Brain Mapp. *30*, 638–649.

Wang, Y.-F., Cui, Q., Liu, F., Huo, Y.-J., Lu, F.-M., Chen, H., and Chen, H.-F. (2014a). A new method for computing attention network scores and relationships between attention networks. PLoS One *9*, e89733.

Wang, Y.-F., Liu, F., Long, Z.-L., Duan, X.-J., Cui, Q., Yan, J.H., and Chen, H.-F. (2014b). Steady-state BOLD response modulates low frequency neural oscillations. Sci. Rep. *4*, 7376.

Wang, Y., Jing, X., Liu, F., Li, M., Long, Z., Yan, J.H., and Chen, H. (2015). Reliable attention network scores and mutually inhibited inter-network relationships revealed by mixed design and non-orthogonal method. Sci. Rep. *5*, 10251.

Wass, S., Scerif, G., and Johnson, M.H. (2012). Training attentional control and working memory – Is younger, better? Dev. Rev. *32*, 360–387.

Wiggins, J.L., Peltier, S.J., Ashinoff, S., Weng, S.J., Carrasco, M., Welsh, R.C., Lord, C., and Monk, C. S. (2011). Using a self-organizing map algorithm to detect age-related changes in functional connectivity during rest in autism spectrum disorders. Brain Res. *1380*, 187–197.

Wu, M., Lu, L.H., Passarotti, A.M., Wegbreit, E., Fitzgerald, J., and Pavuluri, M.N. (2013). Altered affective, executive and sensorimotor resting state networks in patients with pediatric mania. J. Psychiatry Neurosci., *38*, 232–240.

Wylie, K.P., Rojas, D.C., Ross, R.G., Hunter, S.K., Maharajh, K., Cornier, M.-A., and Tregellas, J. R. (2014). Reduced brain resting-state network specificity in infants compared with adults. Neuropsychiatr. Dis. Treat. *10*, 1349–1359.

Yan, J.H., and Thomas, J.R. (2002). Arm movement control: differences between children with and without attention deficit hyperactivity disorder. Res. Q. Exerc. Sport *73*, 10–18.

Zarate, J.M., and Zatorre, R.J. (2008). Experience-dependent neural substrates involved in vocal pitch regulation during singing. Neuroimage *40*, 1871–1887.

Zhang, H., Long, Z., Ge, R., Xu, L., Jin, Z., Yao, L., and Liu, Y. (2014). Motor imagery learning modulates functional connectivity of multiple brain systems in resting state. PLoS One *9*, e85489.