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Executive Function and Brain Region Development in ADHD: Mechanisms and Interventions in the Prefrontal Cortex and Related Circuits

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Abstract:

Attention-deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental disorder in children and adolescents, significantly impacting academic performance, emotional regulation, and social adaptation. Executive function, a higher-order cognitive ability that governs cognition, emotion, and behavior, is a core symptom of ADHD. This article examines executive function deficits in ADHD, focusing on the roles of brain regions such as the prefrontal cortex, parietal lobe, and basal ganglia, and how developmental abnormalities in these areas contribute to the disorder. Research shows that deficits in attention control, impulse inhibition, and working memory are linked to structural and functional abnormalities in these brain regions. By integrating neuroimaging and biological research, this article explores how delays or dysregulations in brain development led to executive function impairments, shedding light on the neurobiological mechanisms involved. Furthermore, the paper evaluates the potential of cognitive training, pharmacological treatments, and behavioral therapies in improving these deficits, particularly by enhancing the function of the prefrontal cortex and other key regions, thus boosting cognitive and behavioral outcomes for ADHD patients.

Keywords:

ADHD
Executive function
Prefrontal cortex and other related brain areas
Neuroplasticity
Intervention strategies

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1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a common neurodevelopmental disorder in children and adolescents, with a prevalence of 6.4% among school-age children in China [1]. Approximately 65% of ADHD cases persist into adulthood [2], affecting learning, emotional regulation, and social adaptation. Executive function (EF), which includes working memory, inhibitory control, and attention regulation, is often impaired in ADHD patients, leading to significant difficulties in attention control, impulse inhibition, and working memory [3]. These deficits severely impact daily life, including academic performance, work, and social interactions.

Recent studies have shown that executive function deficits in ADHD patients are closely linked to developmental abnormalities in multiple brain regions, particularly the prefrontal cortex, as well as the parietal lobe, basal ganglia, and thalamus [4,5]. These dysfunctions contribute to impairments in attention control, impulse inhibition, and working memory in ADHD patients [6]. In response, various intervention strategies, such as cognitive training, pharmacological treatments, and behavioral therapies, have been proposed to enhance the function of these brain regions and promote neuroplasticity, ultimately improving executive function in ADHD patients [7]. This paper further evaluates the effectiveness of these interventions in enhancing cognitive and behavioral performance.

2. Executive function

Executive function, which regulates behavior, emotions, and cognitive processes such as attention control, working memory, and emotional regulation, enables goal-setting, planning, problem-solving, and decision-making in complex situations [8,9]. Its development during childhood and adolescence is critical for academic success, social interactions, emotional regulation, and mental health [10]. As individuals transition into adulthood, executive function continues to impact daily life, career development, and mental well-being, making it central to cognitive, behavioral, and emotional growth.

2.1. Executive function deficits in individuals with ADHD

Individuals with ADHD often exhibit varying degrees of deficits in executive functions, with the most prominent symptoms being attention control deficits, poor impulse control, and insufficient working memory.

(1) Attention control deficits: Attention control deficits: ADHD patients struggle with sustained attention and are prone to distractions [11]. Studies show lower performance on tasks requiring attention, with frequent distractions [12]. These deficits affect academic performance, decision-making, and adaptation in daily life [13], impairing learning and problem-solving.

(2) Impulse control deficits: Impulse control deficits: ADHD patients often struggle with inhibiting impulsive behaviors, such as making quick decisions or reacting emotionally [11]. This deficit hampers emotional regulation and causes interpersonal conflicts. Research shows that ADHD children exhibit stronger impulsive behaviors, leading to unstable social interactions [14].

(3) Working memory deficits: Working memory deficits: ADHD patients struggle with holding and manipulating information over short periods, impairing their ability to multitask and complete long-term tasks [15]. Children with ADHD often fail to integrate information for multi-step instructions, affecting both academic performance and daily planning. These deficits are linked to academic failure, emotional distress, and behavioral issues [16].

3. Impact of executive function deficits on daily life

Executive function deficits in ADHD patients significantly impact their academic, social, and emotional functioning, leading to a range of negative outcomes. Due to attention and impulse control issues, they often struggle with poor academic performance, especially in tasks requiring sustained focus, such as mathematics and language arts [13]. Additionally, deficiencies in working memory hinder their ability to organize information effectively, reducing task efficiency and quality. In social and emotional domains, ADHD patients frequently experience conflicts with others due to impaired impulse control and emotional regulation, which can strain interpersonal relationships. Research shows that children and adolescents with ADHD are more prone to aggressive behaviors, emotional instability, and antisocial conduct, further complicating their social adaptation [14]. The cumulative effects of these deficits not only create academic and social challenges but also carry long-term risks for career success and mental health in adulthood.

4. Neurobiological mechanisms of executive function deficits in ADHD: Functional and developmental abnormalities in brain regions

Recent studies have found that executive function deficits in ADHD patients are closely related to structural and functional abnormalities in specific brain regions, especially the prefrontal cortex (PFC) and its associated neural circuits. Neuroimaging analysis of the brains of ADHD patients has revealed that during tasks requiring executive functions, the relevant brain regions typically exhibit inefficient activity patterns, providing important clues for uncovering the neurobiological mechanisms of ADHD.

4.1. Structural abnormalities

Neuroimaging studies show that ADHD patients often have structural abnormalities in the prefrontal cortex (PFC), including volume reduction and developmental delays [17]. These patients also exhibit lower gray matter density in the PFC, which is linked to their executive function deficits. Inefficient activation of the PFC during tasks requiring impulse inhibition and sustained attention suggests limited regulatory function. These abnormalities impair the PFC's role in attention control, impulse regulation, working memory, and emotional regulation, leading to difficulties in social interactions and daily behavior [18]. Additionally, other brain regions, such as the parietal lobe, basal ganglia, cerebellum, and thalamus, also show structural changes that contribute to ADHD symptoms.

4.2. Functional abnormalities

In addition to structural abnormalities, ADHD patients also show significant functional dysfunctions during executive function tasks. Research indicates inefficient brain activity patterns that are closely linked to ADHD's core symptoms. For example, the functional connectivity between the PFC and basal ganglia often exhibits abnormal low- or high-frequency activity, disrupting their coordinated function [19]. Furthermore, ADHD patients' brain network activity lacks flexibility, leading to ineffective regulation across various tasks. Studies have found inefficient activation in the dorsolateral prefrontal cortex-dorsal striatum-thalamus pathway during "cold" executive tasks, while "hot" executive tasks may involve abnormalities in the orbitofrontal cortex-limbic system circuit [20]. These functional impairments suggest that ADHD is not just due to structural damage in specific regions but also to dysregulation in complex brain networks.

4.3. Relationship between developmental abnormalities and executive function deficits in ADHD

Neuroanatomical studies suggest that delays in prefrontal cortex (PFC) development are key to executive function deficits in ADHD. The PFC, which matures later in life, undergoes rapid changes during childhood and adolescence. In ADHD, these developmental delays hinder both structural and functional maturation, leading to ongoing difficulties in cognitive control and emotional regulation [17]. Limited neuroplasticity in the PFC, influenced by genetic, environmental, and early developmental factors, prevents full maturation of neural circuits, impairing attention control, impulse inhibition, and working memory [21]. This contributes to the persistence of ADHD symptoms into adulthood.

5. Brain networks and ADHD executive function deficits

ADHD involves abnormalities not only in the prefrontal cortex (PFC) but also in multiple brain regions, including the dorsal prefrontal cortex, orbitofrontal cortex, basal ganglia, thalamus, and parietal cortex [22]. The executive function relies on a network of interconnected regions, including the cortical-striatal-thalamic-cortical loop for cold executive function and the orbitofrontal cortex-limbic system loop for hot executive function. These networks support functions such as decision-making, working memory, emotional regulation, and impulse control, essential for maintaining executive function integrity [23].

In addition to the PFC, ADHD involves abnormalities in multiple brain regions, particularly the dorsal prefrontal cortex, orbitofrontal cortex, basal ganglia, thalamus, and parietal cortex. Extensive research indicates that the brain networks supporting executive functions are not limited to the prefrontal cortex; in fact, they involve multiple brain regions with complex interconnections between them [22]. The executive function relies not only on the prefrontal cortex but also on the cortical-striatal-thalamic-cortical loop, which together forms the neural network for executive function. For example, the neural pathways for cold executive function mainly involve the dorsal prefrontal cortex-dorsal striatum-thalamus, while the pathways for hot executive function are formed by the orbitofrontal cortex-limbic system loop. The interaction of these brain networks determines the integrity of an individual's executive function. The dorsal prefrontal cortex-dorsal striatum-thalamus loop primarily supports rational decision-making, working memory, and task planning, which are associated with cold executive function, while the orbitofrontal cortex-limbic system loop is more closely related to emotional regulation, impulse control, and social behavior regulation, which are key aspects of hot executive function [24].

ADHD patients exhibit significant abnormalities in the functional connectivity of brain networks during executive function tasks. Specifically, during cognitive tasks, the coordination between the Default Mode Network (DMN) and Task Positive Network (TPN) is impaired. The DMN, involved in decision-making, working memory, and social cognition, fails to be suppressed during task execution in ADHD patients, leading to its persistent activity, which disrupts TPN function. This inability to downregulate the DMN may contribute to attention deficits and executive dysfunction in ADHD [21].

The abnormal functioning of brain networks in ADHD involves not only the PFC but also altered connectivity between regions like the basal ganglia and thalamus, which are crucial for motor and cognitive regulation. These dysfunctions disrupt executive function, impairing attention, impulse control, and working memory, and affecting daily life and social adaptation.

6. Intervention strategies for ADHD

An increasing number of studies show that intervention strategies targeting executive function deficits in ADHD patients are becoming more diversified and show great potential. Research indicates that through a combination of cognitive training, pharmacological treatment, and behavioral therapy, the executive function of ADHD patients can be effectively improved. These interventions focus not only on enhancing the function of the prefrontal cortex (PFC) but also on optimizing the development and function of other relevant brain areas, aiming to promote the overall cognitive ability of the brain [22,24]. As the understanding of the neurobiological mechanisms of ADHD deepens, more interventions based on the principles of neuroplasticity are continuously emerging, with the expectation of providing more personalized and precise treatment for individual cognitive deficits.

6.1. Cognitive training and the improvement of executive function

Cognitive training, a non-pharmacological treatment, aims to enhance ADHD patients' core executive functions, such as working memory, attention control, and cognitive flexibility. ADHD patients often struggle with working memory, exhibiting limited capacity and slower processing speeds, which impair task execution and decision-making. Cognitive training, particularly focusing on working memory, helps improve the ability to retain and process information [25]. Attention control, another key deficit in ADHD, can also be enhanced through training, improving the ability to sustain focus and resist distractions, thus boosting performance in complex environments [26]. Additionally, cognitive flexibility training helps ADHD patients switch between tasks and adapt to unexpected situations, enhancing problem-solving abilities [27]. Long-term, diverse cognitive training promotes overall executive function improvements by enhancing brain plasticity and the coordination and efficiency of information processing.

7. Pharmacological treatment and regulation of neurotransmitter systems

Medication remains one of the main treatment approaches for ADHD, particularly stimulant medications.

Stimulant medications improve cognitive performance in ADHD patients by regulating neurotransmitter systems in the brain that are related to executive functions. The most used medications are methylphenidate (Ritalin) and amphetamines (Adderall), which enhance the activity of norepinephrine and dopamine to improve executive functions such as attention control, impulse inhibition, and working memory [28].

Research shows that the mechanisms of these medications are not limited to the PFC but also regulate multiple neural circuits in the brain, particularly the cortical-striatal-thalamic pathway [29]. These pathways typically exhibit inefficient neural activity in ADHD patients, and medication treatment improves the functional connectivity of these brain regions by enhancing neurotransmitter activity, thereby restoring executive functions. Medication treatment can significantly improve task performance in ADHD patients in the short term, but long-term effects and dependence remain important issues in both research and clinical practice.

8. Future research directions and personalized interventions

As our understanding of ADHD's neurobiological mechanisms advances, personalized intervention strategies are becoming increasingly promising. Future treatments will be tailored to each patient's unique neurobiological characteristics, such as the PFC's developmental status, brain region connectivity patterns, genetic factors, and cognitive-behavioral performance [17]. Advances in big data, genomics, and neuroimaging will allow for more precise treatment matching. For instance, genomic data can identify genetic markers associated with ADHD symptoms, guiding personalized treatments [28]. Brain imaging can reveal structural or functional changes in areas like the PFC or basal ganglia, linking these alterations to symptom expression [22]. This individualized approach aims to maximize treatment effectiveness while minimizing side effects.

With the continuous advancement of neuroscience and intervention methods, the treatment outlook for ADHD is promising. From the perspective of neuroplasticity, cognitive training, medication, and behavioral therapies can all improve the execution functions and neural circuitry connectivity of patients to varying extents. In the future, with the progress of neuroimaging technology, genomics, and interdisciplinary research, personalized interventions will become possible, offering more precise and effective treatment options for ADHD patients. More importantly, future research will not only focus on the prefrontal cortex (PFC) but also consider the functional changes in other relevant brain areas, aiming to provide comprehensive scientific evidence and clinical support for ADHD treatment.

Disclosure statement

The authors declare no conflict of interest.

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