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Neural Basis of Sense of Space in Autism Spectrum Disorder

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Abstract: Autism Spectrum Disorder (ASD) is a complex developmental disorder marked by variations in cognitive development, with challenges in spatial cognition and navigation. The rise in ASD diagnoses has led research to focus on understanding how changes in neuroanatomy influence the way individuals with ASD perceive and process spatial information. This paper investigates how changes in key brain regions impacts spatial navigation in individuals with ASD. Through a synthesis and analysis of relevant literature, the study shows that spatial perception in individuals with ASD is closely associated with functional changes in these brain regions. The hippocampus is vital for encoding spatial information and forming memories, while the parietal-occipital regions are crucial to spatial localization and visual processing. Moreover, individuals with ASD often rely more on local processing, impairing navigational abilities in dynamic environments. In short, the analysis suggests that interventions like Sensory Integration Training (SIT) can improve spatial cognition and enhance spatial navigation abilities in individuals with ASD.

Keywords: Autism Spectrum Disorder (ASD), Developmental Disorders, Spatial Awareness, Spatial Navigation, Sensory Integration Training

1. Introduction

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder with highly variable symptoms across individuals [1]. Diagnosis of ASD has steadily increased, with approximately 1 in 100 people worldwide now on the spectrum [2]. ASD affects the neurobiology of the brain, leading to differences in how individuals interact with their environment. The ability to perceive and interact with one's environment, both cognitively and physically, is known as spatial awareness, and is vital for functioning in daily life. Given its significance, understanding how neurological differences related to ASD affect an individual's spatial awareness is essential. Although significant research has examined the neural differences in individuals with ASD and addressed cognitive and sensory processing deficits, fewer studies have investigated how these differences impact spatial navigation and contribute to spatial awareness deficits. A deeper understanding of how individuals with ASD perceive their environment could lay the groundwork for creating interventions that enhance their self-sufficiency. This paper explores how changes in brain structure and function in individuals with ASD influence their spatial awareness and navigation, by examining previous research on the neuroanatomical foundations of these abilities.

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2. The neural mechanisms of spatial navigation

2.1. The hippocampus in spatial navigation and memory formation

The hippocampus is essential for spatial navigation and awareness, as it encodes environmental information, a role highlighted in numerous studies. One such study investigated the hippocampus's impact on spatial cognition by observing neural oscillations. In this study, epileptic participants were fitted with intracranial electrodes to monitor hippocampal neural oscillation activity during spatial tasks. They were then exposed to virtual environments and tasked with navigation and location-recall challenges. Anti-seizure medication was administered to minimize confounding variables. Measurements of the neural oscillations showed significant activity of the hippocampus in novel settings [1]. In an animal model study utilizing rats, the impact of lesions in the dorsal (DHC) and ventral (VHC) hippocampus on goal-oriented spatial navigation, both in obstacle-free and obstacle-rich environments, was assessed. Anesthesia was infused into the rats through surgery into either the DHC or VHC, inactivating it. After recovery, the rats were placed in either an obstacle-free or obstacle-rich maze and tasked with spatial recall movements recorded and analyzed. The results showed that inactivating the DHC or VHC impaired goal-directed spatial navigation, particularly in obstacle-rich environments, further supporting the hippocampus' role in spatial tasks [3]. One hypothesis explaining how the hippocampus encodes spatial information is through the activity of hippocampal place cells. Place cells fire in response to specific locations within an environment and create neural maps that help the brain orient itself in space. Notably, the distinct activation of place cells across different locations, even in similar environments, underscores their key role in spatial recognition and navigation [4].

2.2. The occipital and parietal lobes in spatial navigation

Located at the brain's rear, the occipital lobe is key to visual processing and contains pathways essential for perceiving the surrounding environment. Particularly, the occipital lobe is crucial for recognizing both familiar and unfamiliar objects. This primarily takes place in the lower occipital cortex (LOC), where it processes object features like shape, motion, texture, and color. Additionally, it helps establish associations between distinct objects or between novel and known objects [5]. These associations help us recognize objects even when they are partially obscured. To process this information, the occipital lobe works with other brain regions, including the parietal lobe. The parietal lobe, located in the brain's middle, plays a crucial role in spatial navigation by integrating environmental information to guide goal-directed movements and exploration. Parietal lobe damage may lead to optic ataxia, as it disrupts goal-directed movements and causes spatial neglect on the side opposite the lesion, thereby impairing spatial navigation [6]. The severity of spatial deficits varies with the extent of brain damage. A critical region involved is the parietal-occipital junction (OCJ), which plays a key role in both depth perception and object identification. Research indicates that the OCJ becomes active when individuals assess the distance of objects from themselves, highlighting its importance in spatial processing. Moreover, when observing distant objects, the OCJ converts its perceptual understanding into sensorimotor representations, enabling motor coordination and planning [7]. The OCJ remaps far space, enabling interaction with distant objects as if they were nearby. This enhances goal-directed coordination and makes movement through near and far environments more fluid and efficient.

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3. The autism spectrum disorder and impairments in spatial navigation

3.1. Autism Spectrum Disorder in the general population

ASD refers to a spectrum of lifelong neurodevelopmental disorders, with major challenges in social interaction, communication, and behavior [8]. Around 1 in 100 children worldwide is affected by ASD, with diagnoses generally occurring between the ages of 3 and 18 [2,9]. Recently, the number of ASD diagnoses has risen sharply, drawing considerable attention. The increasing prevalence of ASD diagnoses is under investigation to determine whether it stems from revised diagnostic criteria, greater public awareness, or improved understanding of genetic and environmental influences. Though various theories have been proposed, ranging from genetic to environmental causes, no definitive scientific explanation has been established for this rise. According to the DSM-V, a diagnosis of ASD requires impaired social interaction, including difficulties with communication, non-verbal behavior, and interpreting social cues. For example, individuals with ASD may struggle to understand others' facial expressions, body language, or tone of voice, and may find it hard to start or maintain normal social interactions. Another criterion is the presence of restrictive and repetitive behaviors, which may include a strong need for routine and extreme discomfort when routines are disturbed, which can lead to significant distress [9]. In addition, individuals with ASD may experience other symptoms that can deeply affect their daily lives. For example, they may have difficulties in building relationships, adapting to new environments, or coping with changes in their surroundings. Besides, individuals with ASD often struggle with spatial awareness and processing environmental stimuli, making daily navigation and adaptation to new settings challenging. These challenges often require support and adjustments to ease daily adaptation [10].

3.2. Spatial perception characteristics in ASD patients

3.2.1. Diagnostic assessment of spatial perception impairment

Previous studies have shown that some individuals with ASD experience considerable challenges in spatial navigation. To quantify these impairments, researchers often use maze tasks, with earlier studies relying on physical mazes and recent research increasingly adopting virtual maze paradigms. The assessment involves two tasks: navigating a maze to a target location and recalling specific paths from memory. These tasks evaluate individuals' environmental orientation and spatial cue processing abilities [11]. In clinical practice, the adaptation assessment of prismatic glasses (a type of corrective lens used to improve visual integration function) is commonly conducted using the Kaplan Nonverbal Battery (KNB). This test systematically evaluates the visual-spatial processing abilities of ASD patients through nine progressive tasks evaluating visual-spatial processing and adaptation. To ensure comprehensive and accurate evaluation, a dual-track approach combining real-time observation with video analysis is used, allowing for unrestricted time to fully support its validity [12]. Though the KNB provides a practical framework for clinical diagnosis, it was not specifically designed to assess spatial perception, and it has two main limitations. The results may fail to fully reflect an individual's true spatial cognition. And lacks dynamic real-world variables. Developing a standardized spatial perception assessment system is clinically valuable, as it can guide precise interventions, such as targeted sensory integration training, and provide objective support for individualized treatment plans.

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3.2.2. Sensory integration training for children with ASD

In ASD, sensory processing differences (SPD) are common and influence how individuals perceive and respond to their environment. Some individuals experience hypersensitivity, reacting intensely to stimuli such as noise, light, or touch, which can easily lead to discomfort or sensory overload. Others show signs of hyposensitivity, displaying limited responses or appearing unresponsive to sensory input that would usually draw attention [13]. These differences can greatly affect the daily functioning and spatial adaptation of individuals with ASD. However, sensory integration training (SIT) can help lessen these deficits. The theory of SIT is that repeated exposure to specific stimuli encourages the brain to reorganize its cortical mapping [14]. While SIT can be applied in different ways, it generally involves exposing individuals to specific stimuli within a controlled environment to assist them in processing and integrating sensory information effectively [15]. The approach targets sensory systems based on the individual's specific dysfunctions, with a focus on the tactile, vestibular, and proprioceptive systems. The intensity of stimuli is adjusted based on the extent of SPD of the individual. Studies have shown that SIT significantly improves fine motor skills related to proprioceptive movement, such as jumping or running in specific environments [1]. Additionally, by improving subtle visual processing abnormalities, such as object boundary recognition and coordinated movement discrimination, SIT can effectively enhance the spatial navigation abilities of individuals with ASD [14]. Further research is needed to confirm the overall effectiveness of SIT and to better understand how it influences spatial navigation, including its impact on underlying neuroanatomical structures.

4. Brain mechanisms of spatial navigation in ASD patients

4.1. Hippocampal differences in individuals with ASD

The hippocampus plays a vital role in spatial navigation by integrating spatial information and continuously updating cognitive maps. In individuals with ASD, however, studies have identified notable abnormalities in hippocampal structure and function, which may contribute to observed difficulties in spatial processing. Notably, Individuals with ASD often exhibit reduced brain-derived neurotrophic factor (BDNF) levels, likely due to genetic or neurodevelopmental factors [16]. Since BDNF is crucial for synaptic plasticity, dendritic remodeling, and hippocampal neurogenesis, lower levels may directly impair the function of place cells, contributing to spatial navigation impairments in ASD [17]. Interventions such as aerobic exercise, dietary modifications, or certain medications can enhance BDNF expression, offering potential avenues for mitigating these deficits. However, the role of the hippocampus in ASD remains unclear, as structural findings are inconsistent. Some studies report significant abnormalities, while others find no measurable differences, reflecting the heterogeneity of the condition rather than a uniform neuropathological profile.

4.2. Spatial navigation and brain region utilization in individuals with ASD

In terms of spatial navigation, autistic individuals tend to rely more on the posterior aspect of their brain than the frontal aspect, this includes the parietal and occipital lobe. In one study, the visuospatial capabilities of autistic were tested by asking participants to identify missing blocks in figures. The results showed greater activation of the parietal and occipital lobe, with no changes in connectivity between the lobes. In fact, throughout the task, the frontal, parietal, occipital lobes were seen to be communicating as would be expected in a neurotypical individual [18]. This demonstrates

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that while autistic individuals exhibit neurotypical connections, a greater emphasis on the use of the parietal and occipital lobe is present in people with ASD. This is due to the bias towards local processing [18]. Local processing is a behavioral pattern often seen in people with ASD and involves selectively focusing on certain features or elements of an object or environment rather than forming connections between the individual spatial properties. This is relevant to spatial navigation as this means that when navigating their environments, autistic individuals will tend to rely on objects, landmarks or memories of maps to orient themselves [19]. This method of spatial navigation can be problematic as an over-reliance on individual objects or characteristics can lead to a scenario where a person with ASD is unable to navigate an environment missing these objects or spatial cues. For example, in dynamic environments where landmarks or spatial cues are unstable, individuals with ASD may struggle to orient themselves. This issue worsens as dynamic features increase and salient objects decrease. However, interventions like sensory integration can reduce local processing biases, improving ASD individuals' adaptability in dynamic environments and enhancing social cognition.

4.3. Altered inferior temporal gyrus activity and spatial navigation in ASD

In neurotypical individuals, the inferior temporal gyrus (ITG) plays an important and complex role in spatial navigation, particularly when it comes to recognizing characteristics of people and objects [20]. The ITG processes and integrates the different facial features into one coherent representation, which allows for recognition of people and emotions. However, in individuals with ASD, altered activity of the ITG has led to deficits in visual perception and multisensory stimuli integration, that could cause difficulties with emotional processing and facial recognition. Overactivation of the ITG in autistic individuals when recognizing faces, suggests that people with autism see faces as any other object in the environment and as such process them similarly. This increased activation of the ITG when processing faces could explain the difficulties with emotional processing faced by people with ASD [21, 22]. This can hinder spatial navigation by reducing awareness of important spatial features and social cues in crowded environments. For example, emotion recognition plays a crucial role in interpreting environmental cues; for instance, detecting fear or surprise in others can signal potential danger or sudden change. When individuals with ASD have difficulty recognizing these emotions, they may overlook important social and situational information, limiting their ability to respond appropriately to their surroundings. It may also worsen hypersensitivity, further disrupting orientation within the environment. Interventions can help individuals with ASD recognize facial features linked to emotions, which enhances emotional processing. This improvement can lead to better understanding of social cues and interactions with the environment.

5. Methodological approaches to spatial perception in ASD

Individuals with ASD exhibit a broad spectrum of neurological differences, from minor functional changes to pronounced structural abnormalities. This variability highlights the importance of diverse sampling to ensure that research findings accurately reflect the full range of experiences across the spectrum. However, this requirement may give rise to ethical concerns, especially for individuals with severe cognitive symptoms that may not allow for informed consent. While obtaining consent from parents or guardians can address this issue, researchers must ensure clear, ongoing communication with both participants and guardians, explaining the study's purpose and requirements and confirming understanding at each stage. Future research on spatial perception in individuals with ASD should account for these methodological challenges and develop suitable

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adaptive strategies to address them. This includes establishing a stratified sampling framework to capture the diversity of individuals on the spectrum, developing assessment tools suited to a range of cognitive abilities, implementing a dynamic informed consent process to maintain participant engagement throughout the study, and using multimodal communication approaches to ensure clear and accessible information exchange.

6. Conclusion

The complexity of ASD is highlighted by understanding the neural basis of spatial perception in individuals, emphasizing the need for further research to create tailored interventions. The findings in these research studies exemplify how the altered neurological structures of people with ASD affect their spatial navigation abilities, with differences in the hippocampus and inferior temporal gyrus and a reliance on parietal-occipital areas leading to challenges in perceiving and processing the information received from the environment around them. While there currently exists methods to help alleviate these challenges, these interventions are not perfect and may not be beneficial for all those who face spatial navigational challenges. Therefore, by filling in gaps in our current understanding of spatial cognition in ASD, future and current intervention methods can be adjusted to be more efficient and targeted to individuals, allowing for a more fulfilling and successful life.

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