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# Exploring the role of the vestibular system in visuospatial memory in developmental dyslexia: Narrative review

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**ABSTRACT**

Individuals with dyslexia face significant challenges when it comes to writing and reading, even though they can receive an education. Various theories suggest that difficulties in processing auditory and visual cues, crucial for reading, are the underlying cause of developmental dyslexia. The vestibular system intricately processes the visuospatial memory, essential to reading comprehension. This review aims to provide a detailed explanation of the crucial role of the vestibular system in visuospatial memory, cognition, and motor planning.

## Introduction

Developmental dyslexia is a condition marked by challenges in learning to decode and spelling skills. The DSM5 categorizes dyslexia as one type of neurodevelopmental disorder.[1] The nature and meaning of dyslexia have been controversial since its initial identification in the late nineteenth century.[2] Despite the abundance of scientific information concerning dyslexia, there is still an ongoing debate regarding its precise definition.[3,4]

The National Institute of Child Health and Human Development (NICHD) has established a widely accepted definition of dyslexia, which is as follows: "dyslexia is a specific learning disability that is neurological in origin. Difficulties with accurate and fluent word recognition and poor spelling and decoding abilities characterize it. These difficulties are typically caused by a deficit in the phonological component of language, which is often unexpected for other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede the growth of vocabulary and background knowledge.[5]

Dyslexia, a prevalent learning disorder, impacts a substantial proportion of the population, with prevalence estimates ranging from 5% to 17.5%. Several factors contribute to the variation in estimates. The utilization of different operational definitions of dyslexia across various studies can result in divergent prevalence rates. For example, some studies may use more inclusive or exclusive criteria for dyslexia diagnosis. Additionally, environmental variables such as geographical regions and socioeconomic status can influence the prevalence of dyslexia in different populations.[6] A recent comprehensive analysis revealed that developmental dyslexia affects an estimated 7% of the global population. Furthermore, the study showed a

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higher incidence of dyslexia in boys compared to girls.[7] The processing speed, while slower and more variable in males, highlights the unique journey of overcoming challenges in developmental dyslexia, encouraging resilience and growth.[8]

Dyslexia is a chronic condition that manifests differently in each individual, depending on their specific skills and the context in which they are learning.[4,9] Phonological processing is a fundamental component of reading proficiency. This process encompasses identifying and differentiating various speech sounds, essential for adequate speech comprehension. Furthermore, it facilitates the accurate production of sounds during verbal expression. Challenges in phonological processing are the primary cause of dyslexia, which affects an individual's oral language sound recognition and impedes their speech, reading, and spelling abilities.[10] Dyslexia presents a diverse range of characteristics in the individuals it affects. Throughout the developmental trajectory spanning from childhood to adulthood, individuals with dyslexia experience diverse manifestations of challenges. During the early stages of childhood, many individuals encounter difficulties in connecting the sounds they hear to the letters they see. This foundational skill is crucial for their literacy development. As they progress and grow older, they often face more complex challenges, such as reading fluency, where they may struggle to read smoothly.[11]

The literature has proposed numerous theories to explain the underlying causes of dyslexia. Among these theories, the phonological impairment hypothesis is the most prominent explanation for this disorder.[1,12] Some literature suggests that issues in the cerebellum may cause dyslexia. Moreover, the connection between the cerebellum and proficient reading and mathematical aptitude is fascinating.[13-15] Studies have revealed that children with dyslexia exhibit a visual attention impairment and an aberrant oculomotor pattern. [16-18] Drawing from various theories, numerous researchers have devised diverse training methods to enhance the reading capabilities of children diagnosed with dyslexia. This review aims to thoroughly comprehend the vestibular system's role in visuospatial memory in developmental dyslexia. Specifically, it will explore the significance of the vestibular system in enhancing visuospatial skills and its potential impact on individuals with developmental dyslexia.

### *Timeline of developmental dyslexia*

The timeline of developmental dyslexia begins with scientists exploring the possibility of learning disabilities and dyslexia as phenomena in the mid-1800s. Initially, people referred to dyslexia as "word blindness", meaning that the person cannot recognize and understand the words he sees. In 1877, Adolf Kussmaul changed the terminology of "word blindness" to "complete text blindness".[19] The American medical practitioner Samuel Orton (1879-1948) conducted observations that revealed common linguistic challenges experienced by numerous children. These included difficulties distinguishing between the letters p and q, b, and d, a strong inclination for confusing palindromic words, and a notable capacity to read from a mirror. Dr. Orton's research, which involved the study of over three thousand individuals facing language-related impediments, culminated in the identification of these difficulties as "strephosymbolia", a term denoting "twisted symbols.[20] In 1968, the World Federation of Neurology (WFN) provided the following definition for dyslexia: "A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence, and sociocultural opportunity". However, some have criticized this definition as an "exclusion definition," arguing that it could potentially exclude underprivileged individuals or those with low IQs from receiving a dyslexia diagnosis. The Italian scientist Paulesu led a study that looked at dyslexia in people from different cultures and found that the cognitive and biological factors that cause it are the same across all of them.[21]

The term "dyslexia" was first used by Dr. Rudolf Berlin in 1887. It was first defined by Lyon in 1994 and then updated in 2002 to say that it is "a specific learning disorder that is neurobiological in origin and is characterized by difficulties with accurate and fluent word recognition and poor spelling and decoding abilities".[22,23] Before the mid-20th century, the dominant understanding of developmental dyslexia was that it was a hereditary deficit that hindered an individual's capacity to comprehend written language visually. In the 1980s, researchers rejected this hypothesis. The brain's abnormal visual processing and failure to acquire phonological skills have revised it to a language disorder.[12]

In their summary of dyslexia, Peterson and Pennington found it moderately heritable. They also identified candidate genes involved in brain development and highlighted environmental risk factors linked to lower socioeconomic status. They noted common comorbidities like attention-deficit/hyperactivity disorder, speech/ language disorders, and other learning disabilities, all influenced by shared risk factors.[24]

Utilizing advanced brain scanning techniques and analyses, it was indicated that dyslexia is a brain-based and neurodevelopmental disorder, multifactorial and universal.[25,26] Contemporary eye-tracking techniques have yielded valuable knowledge about the operation of the dyslexic brain while reading. These methods can effectively assess the cognitive load experienced by individuals while reading. Furthermore, they serve as a strong foundation for developing predictive and automated models instrumental in screening for dyslexia.[27] Moreover, eye-tracking and text-reading tasks effectively identify dyslexia and other disorders. [28]

### *Neural pathways of reading*

The development of reading skills encompasses several components, including reading speed, fluency, and automaticity.[29] Functional imaging studies prove that recognizing words proficiently relies on an organized cortical system that integrates the processing of orthographic, phonological, and lexico-semantic aspects of words.[30,31] Three primary interrelated systems, orthography, phonology, and semantics, enhance the reading process. These systems involve specific regions of the brain, including the occipitotemporal, temporoparietal, and inferior frontal cortex.[29,31]

Three cortical areas consistently emerge as hubs of the reading network: the left inferior frontal gyrus (IFG), left occipitotemporal (OT) cortex, and left temporoparietal cortex (TP). The left inferior frontal gyrus (IFG) is a brain region essential for language processing and production. This region overlaps with Broca's area, which has long been associated with language production. Activation of the left IFG occurs early in the reading process and understanding of words, indicating its involvement in early phonological processing, which is the recognition and processing of the sounds of words. This early activation suggests that the left IFG plays a critical role in the initial stages of language processing.[29,32]

The left occipitotemporal (OT) region comprises the lingual gyrus and fusiform gyrus, which are involved in word recognition. Researchers have linked the activation of the left lingual gyrus, also known as the medial OT gyrus, to the visual perception of the length of words.[33] The left temporal gyri (TP) areas involved in reading include the supramarginal gyrus (SMG), angular gyrus (AG), and posterior regions of the middle and superior temporal gyri (MTG/STG).[34] The SMG performs functions related to both orthographic and phonological processing, whereas the AG is primarily involved in phonological processing and semantics. The STG overlaps with Wernicke's area, which involves language comprehension and reading-related processes. The left thalamus frequently exhibits activation during reading activities, although it is typically not considered a component of the reading network.[32]

Reading tasks consistently engage the cerebellum, despite its rare inclusion within the conventional reading network. The right crus connects with regions in the left hemisphere, and there are distinct functional and structural differences between typical readers and readers with developmental dyslexia (DD).[13] The cortical reading network comprises the dorsal and ventral reading pathways. The dorsal reading pathway, consisting of the TP regions (left STG, AG, SMG) and the IFG, primarily facilitates the deciphering of words. The dorsal reading pathway overlaps with the dorsal visual pathway. The ventral reading pathway includes OT regions such as the VWFA, the MTG, and the IFG. It is associated with rapid recognition of whole words, usually familiar sight words that do not need to be decoded. Reading acquisition gradually shifts with increasing reading skills from the dorsal to the ventral pathway.[35,36]

***Theories of developmental dyslexia***

There are three categories of theories related to developmental dyslexia. They are psychological, signal-processing, and neurological. The dominant psychological theory of dyslexia is phonological theory, and it hypothesizes that dyslexic children fail to acquire the skill of phonemic awareness, which is responsible for competent reading.[37] Reading involves memory for phonological sequences and word retrieval, which children with dyslexia find challenging. Abnormalities in the left inferior frontal, parietal-temporal, and inferior temporal-occipital areas are linked to the phonological processing deficiency.[38,39] The phonological deficit theory is the most often used explanation of dyslexia, yet not all dyslexics have phonological processing problems because developmental dyslexia is a multifactorial disorder.[40]

The double-deficit approach is otherwise called signal processing theory for developmental dyslexia. It examines phonological and rapid-naming deficiencies in information processing. In 1974, Martha Denckla discovered that dyslexic individuals have slowness at rapid automatized naming (RAN), which is a speech timing and fluency problem.[41] Maryanne Wolf later introduced the 'double deficit' hypothesis, which suggests that individuals with dyslexia have a deficit in both phonological and rapid serial/automatized naming skills. The double-deficit theory, an extension of the dominant phonological deficit theory, proposes that dyslexic individuals have a single deficit in one or a double deficit in both skills.[37,41-43]

People with dyslexia may have a shorter visual attention span, making reading sluggish and inaccurate. In addition, they might experience visual stress, which is a condition that can be uncomfortable when they are exposed to high contrast, coarse black and white stripes. There is a high probability that this results from an excessive stimulation of the magnocellular timing system, which is accountable for rapidly signaling moments when visual events occur.[44]

A recently developed set of neurological theories explores the various brain structures involved in developmental dyslexia. The magnocellular and cerebellar theories are significant in neurological theory as they provide insights into the functions and dysfunctions of the magnocellular and cerebellar pathways in the brain, contributing to our understanding of various neurological conditions and cognitive processes. According to the magnocellular theory, the visual magnocellular neurons play a crucial role in quickly processing visual attention.[37] Neuroimaging studies have demonstrated that irregularities in the magnocellular layers of the lateral geniculate nucleus result in atypical binocular control and visuospatial attention.[39]

Even though more evidence supports the magnocellular theory, it does not compete with phonological theory for three reasons: 1) any dyslexics can learn to read well despite poor magnocellular function and without visual problems, 2) the dorsal attentional and visuomotor pathways are not strictly composed of magnocellular characteristics, and 3) the preponderance of evidence was correlational, indicating that a conclusive cause-and-effect relationship could not be firmly established.[37] A cerebellar deficit hypothesis suggests that the cerebellum plays a significant role in retrieving words from semantic memory and, thus, in decoding performance due to its connections with the dorsal and ventral reading pathways. Dysfunction in the cerebellum may raise the likelihood of experiencing developmental reading disorders.[14] According to numerous theories, dyslexia is believed to arise from a chain of impairments that stem from a singular “core deficit”. Proficient reading necessitates swift communication among a dispersed network of visual, auditory, and language processing systems. Any impairment in these systems could result in challenges when acquiring a sophisticated skill such as reading. To address the challenges associated with dyslexia, it is essential to utilize a multiple-model system. This approach can help prevent the overprediction that often occurs when relying solely on a single deficit model.[40]

### *The significance of visual working memory and visual-spatial abilities in the reading process*

The relationship between visual-spatial skills and reading abilities is a subject of ongoing debate. Visual-spatial ability encompasses a complex cognitive skill set, incorporating spatial perception, visualization, and mental rotation. The functions encompass mental imagery, navigation, distance and depth perception, and visuospatial construction, and they represent the brain’s highest level of visual processing and rely on the proper functioning of the parietal cortex, a region of the brain responsible for integrating sensory information.[45]

Reading entails a range of cognitive processes, including the visual recognition of word forms and eye movements. Fixations and saccades are two types of eye movements utilized to extract visual information from text. These processes activate phonological, syntactic, and semantic information, enabling readers to access their mental lexicon and comprehend the text. Working memory (WM) significantly influences these cognitive processes, and disparities in WM capacity among individuals can predict their reading ability.[46] Working memory is an executive controller that interacts with distinct short-term storage systems for auditory-verbal and visuospatial information, in line with the multi-component model. In 1974, Baddeley and Hitch put forth a multicomponent working memory model. This model proposes the existence of an attentional controller known as the central executive, along with two subsystems: the visuo-spatial sketchpad, responsible for visual storage and processing, and the phonological loop, accountable for handling acoustic and verbal information.[47]

The phonological loop and the visuospatial sketchpad are components of Visual Working Memory (VWM) and are linked to long-term memory via the episodic buffer. The episodic buffer is the intermediary between working memory (WM) and long-term memory. The study conducted by Pham and Hasson (2014) examined the components of working memory in the reading process and found that visual working memory plays a crucial role in reading comprehension. The study revealed that VWM capacity notably impacted reading fluency during the initial reading performance. However, it did not have a significant influence on the rate of change over time.[48] VWM measures are strongly linked to EWM, and the first reading represented a new and challenging task that required participants to use their executive cognitive abilities.[49]

The academic performance of primary school students is indirectly influenced by their visuospatial memory, which acts as a mediator for their arithmetic and reading abilities. Neuroimaging studies have indicated that the neural circuits in the brain’s left hemisphere support the process of converting graphemes to phonemes in alphabetic writing systems.[50] Conversely, the right hemisphere is responsible for visuospatial processing.[47,49] Franceschini *et al*. found that visual-spatial attention influences learning to read. Poor readers made more errors on visual search tasks and didn’t benefit from valid spatial cues.[51]

Visuospatial and visual working memory are essential for reading and writing. An individual’s visual working memory capacity and effectiveness in transferring information to long-term memory uniquely contribute to the variations in learning abilities among individuals.

### *Role of visuospatial memory in developmental dyslexia*

Recent updates to the reading model propose that not only the phonological system deficit but also an executive function deficit is a contributing factor in developmental dyslexia. This executive function encompasses working memory and cognitive flexibility, suggesting that these mental processes play a crucial role in dyslexia. So, dyslexia is considered a multifactorial disorder.[52]

Visual attention impairment significantly contributes to the reading challenges in individuals with developmental dyslexia.[53] According to a study conducted by Taran *et al*. in 2022, it was indicated that the brain regions associated with visual attention have a significant impact on the reading abilities of individuals with dyslexia as well as those without dyslexia.[52] This suggests that visual attention plays a crucial role in reading and may have implications for understanding and addressing reading difficulties. In the initial phases of education, complex visuospatial abilities are essential for recognizing letters and words. In instances of developmental dyslexia, a deficit in these abilities can disrupt academic achievement. Furthermore, during subsequent educational phases, broader perceptual impairments may impede the reading abilities of children with DD.[54]

Working memory is an essential determinant of learning and accounts for differences in reading and writing abilities among elementary school children. In a long-term study, it was observed that there was a strong connection between verbal and visual-spatial working memory and word reading accuracy in the first and second grades. However, as the students progressed to fifth grade, none of the measures of working memory showed any significant correlation with word reading accuracy.[55] In a meta-analysis, verbal working memory had a stronger correlation with reading than visuospatial working memory, specifically after the third grade. The relationship between working memory and word recognition was more substantial than between working memory and nonword reading.[56,57]

Individuals diagnosed with dyslexia may exhibit heightened global visual-spatial processing abilities, enabling them to perceive impossible figures more quickly and accurately than those without the condition. Notably, research indicates that individuals with dyslexia may harbor additional talents extending beyond rapid global visual-spatial processing. These findings have significant implications for developing more targeted educational strategies and career guidance tailored to capitalize on the strengths of individuals with dyslexia.[58] A study carried out by researchers at Haskins explored the cognitive and neural underpinnings of visuospatial processing abilities in adolescents with dyslexia in comparison to their typically developing peers. The research findings revealed that individuals with dyslexia demonstrated a visuospatial processing advantage, manifested as reduced response times and comparable accuracy levels when performing a task involving the processing of geometric figures.

The initial stages of word processing rely on verbal and visuospatial working memory. When this process encounters difficulties, the brain may employ visuospatial skills as a compensatory mechanism, enhancing individual learning. However, it does not necessarily contribute to improving the reading process. Consequently, strategies aimed at coordinating verbal and visuospatial skills during the early stages can aid children with dyslexia in enhancing their reading abilities.

### *Significance of the vestibular system in visuospatial memory*

Maintaining the body's equilibrium in the gravitational field is the primary function of the vestibular system. For gaze and postural stability, it is necessary to integrate multiple sensory systems, including vestibulo-ocular tracts, vestibulo-colic tracts, and vestibulo-spinal tracts.[59] The vestibular system comprises two types of sensors: the saccule and utricle, referred to as otolith organs, responsible for sensing linear acceleration, and the three semicircular canals, which detect angular acceleration in three different planes. When functioning correctly, it integrates subconsciously with vision, proprioception, and other sensory functions to create a seamless motion experience.[60]

In 1988, Levinson conducted a study exploring the vestibular system's significance in learning disabilities. He posited that the cerebellar-vestibular system is crucial in coordinating peripheral and central vision, potentially responsible for the limited perceptual span or tunnel vision. Lastly, he proposed the cerebello-vestibular basis of the learning disability hypothesis.[61] Typically, normal children showed better stability in eye movements when fixating on small targets, as well as greater vergence amplitudes and less fixation instability than dyslexic children.

Various literature suggests that the normal development of cognition and learning depends upon the functional vestibular system.[61-64] A 2008 study by Franco and Panhoca found that children exhibiting poor academic performance demonstrated a greater chance of experiencing vestibular dysfunction.[62] This dysfunction is linked to cognitive functions such as visuospatial ability, attention, executive function, and memory. It may cause atrophy in the cortical vestibular network, including the hippocampus, leading to impaired memory and visuospatial ability. Additionally, more attentional resources are required to overcome postural instability after vestibular dysfunction, potentially reducing resources for cognitive tasks.[63]

The alternate smooth-pursuit, saccadic eye movements, and fixations are essential for visual motor skills and influence reading and writing. The vestibular-ocular reflex is responsible for eye movement while moving our head. The integration of ocular and vestibular interconnections is required not only for saccadic and pursuit but also for visual monitoring and performance concentration activities. Based on current evidence, it has been found that eye movements and the vestibular-ocular reflex could potentially hinder one's ability to read and write effectively.[65] The vestibular system enables the enhancement of subsequent visual judgments using multisensory modulation, which involves the convergence of multiple sensory inputs.[66] The vestibular system activation might improve the consciousness and attention of the children, and it would be helpful for children suffering from dyslexia.[67]

In their study, Marchesin *et al*. identified irregularities in the ability to voluntarily control saccadic eye movements across various conditions, including dyslexia, learning disorders, and ADHD.[68] Vestibular stimulation positively affects serotonin levels in the brain, promoting the growth of dendrites and synapses in hippocampal pyramidal neurons. It also inhibits the HPA and SAM axis, reducing stress levels that enhance learning and memory.[64]

Individuals suffering from unilateral or bilateral vestibular loss commonly exhibit a deficit in visuospatial working memory. This deficit is evident across all age demographics and demonstrates a propensity for exacerbation with advancing age. This deterioration is attributed to the diminished functional capacity of the vestibular system, contributing to a progressive decline in cognitive function.[69]

A recent study has discovered that brief vestibular and cognitive training enhances the reading speed of children with dyslexia and that improvement persists after one month. This study demonstrates the significant involvement of the vestibular system in developmental dyslexia. It highlights that dyslexia is influenced by deficiencies in gaze stabilization, impaired visual attention, and deficits in working memory. This study did not differentiate between vestibular and cognitive training, which are commonly responsible for improvement.[16]

## Conclusion

Visuospatial memory, which involves the ability to remember and process visual information about objects and their spatial relationships, is crucial for improving reading and writing, as suggested by various sources in the literature. The vestibular system regulates this type of memory, an intricate network of structures in the inner ear that contributes to our sense of balance and spatial orientation. Individuals with dysfunction or impairment in the vestibular system may encounter challenges related to developmental dyslexia and other neurodevelopmental disorders, which can affect their ability to read, write, and comprehend information. According to the findings of this review, it is suggested that the vestibular system may significantly impact developmental dyslexia. Furthermore, therapy based on the vestibular system has the potential to aid children suffering from this condition

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