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NEUROLINGUISTIC PERSPECTIVES OF PHONOLOGICAL PROCESSING IN DYSLEXICS

Review paper
https://doi.org/10.17234/9789533791821.18

People with reading difficulties have different anatomical and functional brain structures. From a neurological point of view, dyslexia has been characterized by previous studies as the impossibility of proper functioning of the posterior region of the left hemisphere of the brain during reading. The paper describes findings of various neurolinguistic studies confirming a disruption in functional connectivity within the posterior regions in the brain activated during reading in subjects with dyslexia, that is, a separate connection within the visual path and between the area of visual association and prefrontal areas for attention. It also focuses on research of increased functional connectivity within the right hemisphere, reduced functional connectivity in the area of visual word formation and constant functional connection of the anterior areas around the lower front gyrus related to language processing. Understanding the neurolinguistic differences of people with dyslexia may have pedagogical implications for education and curriculum designers.

Keywords: neurolinguistics, dyslexia, language processing, brain structure, functional connectivity

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INTRODUCTION

The most widely accepted theory of dyslexia's cause is the one that explains dyslexia as cognitive difficulties, implying that dyslexia manifests as difficulties in recognising and processing voices and syllables, which then affects language acquisition (Boets et al., 2007, 2008; Frith, 1999; Goswami, 2016; Peer & Reid, 2003; Snowling, 2000). Reading and writing are sophisticated cognitive skills that involve decoding and comprehending a language through phonological awareness. Hickok and Poeppel (2007) suggested a dual pathway of speech process theory according to which the visual system is constructed of ventral and dorsal pathways. The model is composed of the Wernicke area, Broca area, and dorsal and ventral pathways (Pugh et al., 2000, 2001; Shaywitz & Shaywitz, 2008). The superior longitudinal and arcuate fasciculi make up the dorsal route, which corresponds to the processing of phonetic information. The ventral route refers to semantic information processing and is comprised of the inferior frontal occipital, uncinate, and inferior longitudinal fasciculi. Processing the language is, therefore, a highly complex activity. When speaking of speech production, Wang and his colleagues describe a scheme of the language processing activities and the Levelt-Roelofs-Meyer model of speech production:

> "According to the Levelt–Roelofs–Meyer (LRM) model, speech production is divided into six stages. When the picture of a goat is seen, the occipital lobe shows activation after the presentation of the visual information. Next, the visual word form area becomes activated to complete the visual recognition of the image, and the anterior to the middle part of the middle temporal gyrus becomes activated to complete the conceptual preparation and lemma retrieval process. The time window for the conceptual preparation process, which is responsible for converting the visual information into the concept of a goat, is about 0–200 ms. The time window for the lemma retrieval process, which is responsible for further transforming the concept into the word of goat, is about 200–275 ms. Next, the posterior part of the middle temporal gyrus and the STG become activated to complete the phonological code retrieval process. This step takes approximately 275–390 ms, during which the word goat is translated into the correct phoneme[1]. The phoneme is the smallest phonetic unit in language system that can distinguish a word[2]. Before the end of the phonological code retrieval process, Broca area becomes activated to complete the phonological encoding process. This step takes approximately 355–455ms and is responsible for creating the syllable sound and the rhythm information. Before the end of the phonological encoding process, the ventral premotor cortex becomes activated to complete the phonetic encoding process, which has a time window of approximately 410–600ms. This step is responsible for sequencing syllables and the coordinated movement of articu-

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[1] The 'correct phoneme' refers to the word's form encoded at this stage as a sequence of phonemes.

[2] The phoneme is actually a phonological unit. It is also not the smallest distinctivephonological unit, since distinctive features are smaller.

> lators. Finally, the ventral sensory motor cortex activates to control the movement of the articulators and complete articulation." (Wang et al., 2021: 4)

Broca area (Brodmann area 44 and 45) is located in the frontal lobe of the linguistically dominant (usually left) hemisphere, and the lower front gyrus in Broca area oversees articulation and linguistic analysis. Injury to this area causes Broca (motor) aphasia. The Wernicke area (Brodmann area 22) is located in the temporal lobe of the linguistically dominant hemisphere and is considered a center for the understanding and reception of speech and language. Injury to this area causes Wernicke (sensory) aphasia, which causes a person to misunderstand the speech they hear and to produce fluent, but incomprehensible and meaningless speech (Hickok, 2022). The supplementary motor area or premotor region (Brodmann area 6) is located on the front of the motor cortex. Images of positron emission tomography (PET) detect that it is activated during various motor tasks, especially in internally motivated motor movements. Findings of research on developmental and acquired dyslexia imply the differences in functionality of language processing pathways (e.g., Benson et al., 1973; Duane, 1991; Farris et al., 2011; Geschwind, 1970; Horowitz et al., 1998; Shaywitz et al., 2002, 2006) which will be further explained in following text.

DYSLEXIA AND THE BRAIN

The right hemisphere is specialized in visual-spatial data processing, spatial awareness and analyzing the perception of letters and words. The left hemisphere is, in most right-handed people, responsible for language. During reading, there is a joint activation of both hemispheres of the brain. According to the so-called *Novelty model* developed by Goldberg and Costa (1981), new information is processed in the right hemisphere and familiar information in the left. Furthermore, Bakker (1990) developed a model of reading equilibrium, the so-called *Balance Model of Reading*, by which reading begins in the right hemisphere and is transferred to the left when letters and words become familiar. The left hemisphere regulates processes related to syntactically segmenting a language while the meaning to those language rules and the appropriate manner in which to use them is formed within the right hemisphere (Sastra et al., 2019; Theofilidis, 2021). The right hemisphere is better adapted to processing items of several modalities, such as connecting graphemes and phonemes, which require visual and auditory ability. It is reasonable to conclude that there is a developmental process in which literacy (in the first and other languages) begins with increased involvement of the right hemisphere and then moves to the left hemisphere. The developmental shift from the visual-spatial reading strategy to the semantic-syntactic reading strategy seems parallel to the developmental shift from the dominance of the right hemisphere to the dominance of the left hemisphere of the brain during the reading process (Bakker, 1995).

According to Phonological Deficits Theory (Snowling, 2000; Shaywitz & Shaywitz, 2005; Vellutono & Fletcher, 2005), children with dyslexia have difficulties developing phonological decoding skills and do not have adequate knowledge of the relationships between graphemes and phonemes by which to recognize words. Dyslexic children can have various types of cognitive impairments, with phonemic segmentation and phonological memory being the most responsible for reading-related issues. (Kormos, 2017; Frith, 1999; Torgesen et al., 1999). Speech abilities may be influenced by factors similar to those influencing letter decipherment. According to the motor theory of speech perception (Duane, 1991; Theofilidis, 2021), the production of speech is necessary to understand the voices we hear, and it requires a certain anatomical structure (Liberman & Mattingly, 1989). A similar structure-function relationship can exist for early reading, and this system can be anatomically subordinate to a speech system. Disturbances in this structure-function relationship exist in people who have difficulty mastering the skill of reading.

Helenius and her colleagues (Helenius et al., 2000 in Mildner, 2007) investigated adults with dyslexia and found that they had a 100 millisecond slower reaction during the analysis of the semantic acceptability of the test word relative to the context of the sentence which they explained as the impaired pre-semantic stages of word processing. They also found that the neural reactions of dyslexics were significantly weaker, indicating less coordinated neural groups that are activated during reading with comprehension. The primary differences were seen in tasks that required respondents to assess whether the next word was semantically incorrect yet contained the same letters as the exact word, as well as whether that word was semantically and orthographically inappropriate for the sentence's context. Dyslexics reported significantly lower brain activity when the test word had the same first letter as the correct words but was semantically incorrect compared to when the test word was both semantically and orthographically incorrect. From all the above, the authors concluded that the subjects from the control group understood the word as a whole, while the subjects of the dyslexic group relied on sub-lexical word recognition (referring to constituent parts of words). Nonetheless, findings of more recent studies suggest that intra-individual characteristics should also be taken into consideration. A semantic route to reading (alongside the non-lexical reading route and the lexical non-semantic route) may, actually, be dyslexics' strong point. Lukic and her colleagues

(Lukic et al., 2023) discovered that in addition to the cognitive differences among primary school dyslexic students with tested for semantic fluency, the dynamic resting-state functional connectivity differed between the high and average groups in a bilateral fronto-temporo-occipital network. Findings of their research show that semantic fluency performance is strongly linked to specific executive function subdomains and a semantic resting state brain network, caused by inter-individual differences.

LOBES

Pugh and his colleagues (Pugh et al., 2000) found that effective readers' brain activation rose systematically in proportion to the complexity of orthographic-phonological text processing, whereas dyslexic readers' activation did not. In dyslexics, the posterior dorsal temporo-parietal (TP) and ventral occipito-temporal (OT) components of the brain involved in the processing of written text were damaged, their activity was reduced, and their functional connectivity was interrupted. The compensatory and behavior patterns of dyslexic readers include greater reliance on the inferior frontal gyrus (IFG) and more frequent activation of areas in the right hemisphere that undertake the function of circular activation of the posterior areas of the left hemisphere. Pugh and his colleagues (ibid.), therefore, developed a model by which the development of functional circuits (circular functional activation) in the posterior area of the left hemisphere of successful readers, especially in the ventral OT region, depends on a well-organized integration of phonological and lexical-semantic features of words within overlapping neural circuits. They also believe that this integration rests primarily on intact processing of information in the OT system. This developmental trajectory is interrupted in the TP area of the brain of dyslexic readers. The transition to the IFG in dyslexic persons indicates a compensatory procedure that attempts to enable phonological word processing. Dyslexic persons develop this additional (and independent) nonphonological visual-semantic coding pattern in order to grasp the semantics of the text they read. The atypical OT system prevents the development of skillful reading in dyslexic people, but the transition to an auxiliary system supports only marginal and slow word reading.

Pugh and his colleagues consider fluent reading to be related to the functional integrity of the two posterior systems of the left hemisphere: the TP and ventral OT systems (Pugh et al., 2001). These posterior systems are damaged in people with dyslexia who rely heavily on the lower anterior and posterior regions of the right hemisphere, presumably as compensation for the dysfunctionality of the posterior regions of the left hemisphere. The authors state that the TP system initially dominates in people without reading difficulties and is associated with aspects of information processing that are critical in acquiring the skill of integrating the orthographic, phonological, and lexical-semantic aspects of the script. During the acquisition of the skill of increasingly fluent reading, the OT system of skilled readers eventually creates a fast system for fluent word recognition.

Shaywitz and his colleagues (Shaywitz et al., 2002) conducted a study aiming to determine the brain activity in the posterior systems of the brain during reading. They tested children with developmental dyslexia during three different reading tasks: ones in which decoding skills were required, tasks of rhyming pairs of meaningless words, and tasks of determining semantic categories of words. The authors found significantly higher activation of the dorsal parts of the TP areas and ventral parts of the OT areas in the control group as opposed to the dyslexic group of children. The analysis of the gathered data revealed that success in reading positively correlated with activation in the posterior regions, especially in the left OT region. Shaywitz and Shaywitz (2008) also investigated how dyslexic children read meaningless words (or pseudowords) and discovered that reading systems in people with dyslexia are located more in the posterior medial region, while in people without such difficulty they are located more in the anterior lateral OT region. A similar situation occurs when reading Japanese scripts *kana* and *kanji*. During the reading of the Japanese *kana* and *kanji* letters, the left anterior OT region is activated. The *kana* letters are composed of symbols similar to the alphabetic script. In *kana* and alphabetic script, children first learn to read by connecting graphemes to phonemes, and over time these connections are integrated as word forms. During the reading of the *kanji* letter, the posterior medial OT region is activated. The *kanji* letter is composed of ideographs and each sign must be remembered separately, which means that the posterior medial OT region will function as part of a memory-based system.

Olulade and his colleagues (Olulade et al., 2015) explored the differences in anterior-to-posterior gradient of increasing selectivity for words in the left OT cortex in typically reading children and in dyslexic children. The findings of their research suggest a pattern of increasing word selectivity along the medial-to-lateral axis of the left inferior frontal cortex in typically reading children, as well as functional connectivity between the most lateral aspect of this area and the anterior aspects of the OT cortex. Furthermore, they discovered that dyslexic children do not have an inferior frontal cortex gradient and have connectivity between the lateral side of the inferior frontal cortex and the anterior OT cortex.

GYRUS

Changes in the area of gyri in people with reading difficulties have also been extensively explored. Horowitz, Rumsey, and Donohue (1998) found that connections of angular gyrus with the occipital and temporal regions in the left cerebral hemisphere were stronger in successful than in dyslexic readers. Pugh and his colleagues discovered that effective readers had stronger activity in the IFG and other parts of the frontal lobe, as well as an increased demand for phonological processing (tasks involving non-word rhyming), whereas dyslexic readers had no such change. Dyslexic people's left hemisphere functional connectivity was weak when reading words and non-words, but there was no dysfunction in solving metaphonological determination tasks or complex visual-orthographic coding, so the authors conclude that dysfunctionality in the left hemisphere's posterior systems manifests itself only in circumstances that require the transition from orthographic to phonological processing. Their conclusions are confirmed by findings of a research conducted by Farris and his colleagues (Farris et al., 2011). By analyzing the results of functional magnetic resonance imaging (*fMRI*) obtained during the active state and resting state of 15 subjects, a functional relationship was revealed between the inferior frontal lobes in subjects who did not have reading difficulties as well as in subjects with dyslexia who had logographic therapy effects. Such a functional relationship was not observed in subjects with dyslexia who were not affected by the therapy.

Based on fMRI scans of the dyslexic and control group of subjects, Boulanouar and colleagues (Boulanouar et al., 2000 in Mildner, 2007) discovered the bilateral activation of the upper temporal gyrus in the control group during listening to syllables, unlike the activation in the middle temporal gyrus in dyslexic subjects. When they included /pa/ syllables among the /ta/ syllables, the supramarginal gyrus did not activate the same in dyslexic subjects when compared with the control group subjects. Shaywitz and his colleagues (Shaywitz et al., 2002) also found differences in the activity of IFG, as well as supplementary motor area, between dyslexic and control groups. In dyslexic children, unlike the control group, the activation of the IFG during rhyming assessment tasks (phonological task) increased with age, which would mean that Broca area could eventually gain a more significant role in the reading process. The authors conclude that dysfunction of the posterior areas in the left brain responsible for reading exists at the outset of gaining the skill. The activation of the frontal areas in dyslexic persons relates to age, and older children rely more on the IFG, which the authors also see as a compensating mechanism. In people without reading disabilities, compensation occurs in the anterior areas so the differences between older successful readers and dyslexic readers are limited to two posterior areas: PT and OT (Shaywitz et al., 2002, 2006).

ALPHABETIC SCRIPTS, LOGOGRAPHIC SCRIPTS, AND DYSLEXIA

Languages differ, among others, according to the complexity of the grapheme-phoneme relationship and the script used in writing. Slavic languages (such as Russian, Slovak, Macedonian, and Croatian) have a transparent orthography, which means that one grapheme typically represents one phoneme. Languages with opaque orthography and complex grapheme-phoneme relationships (such as English, French, or Nordic languages) are more challenging for students with reading difficulties to learn. (Fišer, 2019; Kormos, 2017). Many studies in neurolinguistics rely on dyslexic subjects reading pseudo- or non-words, but it should be taken into consideration that difficulties with reading such words are mainly found in the English language of opaque orthography and cannot be applied directly to languages of more transparent orthographies (Richland, 2012). Bolger, Gandour and their colleagues (Bolger et al., 2005; Gandour, 2005; Gandour et al., 2003) reviewed findings of research related to languages of different orthographies and scripts in relation to dyslexia. They evaluated 43 scientific articles on various languages to uncover substantial cross-language differences in activations in the left middle frontal gyrus, temporo-parietal area, and right fusiform cortex. Results revealed that processing of the logographic system activates the right OT region more than when processing of the alphabet (Bolger et al., 2005). It is obvious that the Chinese characters require more visual-spatial neural processing than the alphabet's linear connection of letters. Additionally, research shows more activation in the left posterior superior temporal region in using scripts of transparent orthography (e.g., Italian), unlike in less transparent languages (e.g., English) with more activation in the left posterior inferior temporal gyrus. However, the inferior dorsal parietal lobule is more active when writing Chinese (non-transparent orthography). Despite the differences in logographic scripts (e.g., Chinese) and syllabic orthographies (e.g., Japanese), the phonological processing is still an essential element in the process of reading (Kormos, 2017).

CONCLUSION

Dyslexia affects various aspects of life due to difficulties in memory, organization, speed of information processing, automation, emotional state, perception, etc. It is most often diagnosed when mastering reading and writing skills. Teachers are expected to recognize the difficulties students face and approach them with appropriate teaching techniques, but findings of research worldwide indicate insufficient teacher training to identify and teach students with dyslexia (e.g., August & Shanahan, 2008; Erdeljac & Franz, 2012; Fišer, 2019; Moats & Foorman, 2003; Nushi & Eshraghi, 2023; Schneider, 1999). According to the Phonological Deficit Hypothesis, phonological processing of language is still a requisite for mastering reading skill despite the differences in the orthographical representation of languages. Barquero, Davis and Cutting (2014) reviewed the literature related to neuroimaging of reading intervention, that is fMRI studies of pre- and post- intervention scanning data of children with dyslexia. They discovered that such interventions caused normalization in many areas such as: left and right IFG, superior and middle frontal gyri, temporal gyrus and middle temporal gyri, inferior temporal gyrus, inferior parietal lobule, supramarginal gyrus and angular gyrus, and OT region. Fišer (2019) concluded that understanding the origins of dyslexia can aid in teaching English, one of the most difficult languages to teach, in addition to the obvious benefits of neurolinguistic research on speech and language processing among dyslexics for developing intervention therapies. Understanding that there are neurological differences among dyslexic readers and readers without such difficulties may emphasize the need to develop different pedagogical and educational approaches in designing the curricula related to reading skills. It may also help to emphasize the need to expand the existing syllabuses of future language teachers' programs at tertiary level education with the knowledge of neurolinguistic background of dyslexia in order to change the possible negative emotional impact teaching dyslexic students may have on them in the future course of their work experience.

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