

Theories of Dyslexia: Support by Changes in Auditory Perception¹

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ABSTRACT - This study aims to examine contemporary theories on dyslexia, based on findings related to changes in auditory processing and speech perception found in dyslexics. The support for the phonological, allophonic and auditory deficit theories of dyslexia is discussed based on findings related to these changes in auditory perception. A new theoretical model is proposed, according to which dyslexia is a multifactorial-based deficit, with a gamut of associated behavioral symptoms. The deficit presented by dyslexics is partially linguistic, as advocated by the phonological theory, and partially auditory, as advocated by the theory of auditory deficit. Both factors interact and are inseparable in accounting for the symptomatology observed in reading and writing disorders.

Keywords: dyslexia, auditory processing, speech perception

Teorias da Dislexia: Sustentação com Base nas Alterações Perceptuais Auditivas

RESUMO - Este estudo teve por objetivo examinar teorias contemporâneas da dislexia, com base nos achados sobre as alterações no processamento auditivo e na percepção de fala em disléxicos. A sustentação das teorias fonológica, alofônica e do déficit auditivo é discutida a partir dos achados sobre essas alterações perceptuais. É proposto um novo modelo teórico, segundo o qual a dislexia é um distúrbio multifatorial, com uma gama de sintomas comportamentais associados. O déficit apresentado pelos disléxicos é em parte linguístico, como enunciado, na teoria fonológica e em parte causado pela alteração perceptual auditiva, como prevê a teoria do déficit auditivo. Ambos os fatores interagem e são indissociáveis na explicação da sintomatologia observada no transtorno de leitura e escrita.

Palavras-chave: dislexia, processamento auditivo, percepção de fala

Dyslexia is a persistent neurobiological disorder of genetic origin, where family history is one of the most important risk factors. It is one of the most frequent disorders affecting academic performance. The estimated incidence on the population in general ranges from 5% to 10% (Jucla, Nenert, Chaix, & Demonet, 2010). Also known as developmental dyslexia it is traditionally defined by the discrepancy between reading skills and the intellectual capacity of children receiving proper instruction. Despite having intellectual capacity compatible with the age and receiving proper instruction, dyslexics have important (and unexpected) difficulties to learn reading.

The core feature of dyslexia, consistently and systematically found in case studies and study groups, even when compared to controls with same reading skill levels, is the deficit of phonological awareness and on the phonological route of reading (Bogliotti, Serniclaes, Messaoud-Galusi & Charolles, 2008). Goswami (2015) defines phonological awareness as the capacity of thinking over the sound elements that make up words. The phonological route is characterized by the segmented decoding of words,

through the grapheme-phoneme conversion. There is a large body of evidence that the domain of the relationship between graphemes and phonemes is crucial to successfully learn reading and writing. Main evidences are based on longitudinal studies that found that individuals later diagnosed as dyslexic performed low in phonological awareness, even before starting the process of acquiring reading and writing skills; studies that investigated the efficacy of training based on the grapheme-phoneme correspondence; and, studies that showed that dyslexics have serious difficulty of reading without assistance of the lexical knowledge (reading pseudo-words) (Bogliotti *et al.*, 2008).

The origin of the dyslexics' phonological deficit is object of intensive debate. Some authors suggest it is the primary picture of the dyslexia symptomatology. Other authors believe this deficit would be secondary to a more elementary. This study aimed to discuss three contemporary explanatory theories of dyslexia, based on findings about alterations in auditory processing and speech perception in dyslexics. Firstly, we will present the phonological, allophonic and hearing deficit theories. Further, we will discuss the findings about auditory perception changes and their implication to the different theories. Finally, a new theoretical model will be proposed.

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Dyslexia's Explanatory Theories

Phonological Theory

This theory postulates that dyslexics have a specific deficit in the representation, storage and retrieval of the speech sounds, and that the ability of attending to and manipulating linguistic sounds is crucial for the establishment and automation of the graphophonetic relation underlying the skills of phonologic coding and decoding (Landerl & Willburger, 2010; Ramus *et al.*, 2003).

According to Peterson and Pennington (2012) the phonological deficit presented by dyslexics results from an unclear and degraded phonological representation. If speech sounds are poorly represented, stored and retrieved, learning graphophonetic relationship is compromised. The advocates of this theory agree on the core and causal role of phonological deficit in dyslexia. Therefore, this theory postulates the specificity of phonological deficit, i.e., the existence of a direct link between linguistic cognitive deficit (that would be the primary deficit) and the dyslexic's behavior (Ramus *et al.*, 2003). The evidence that supports this theory stems from studies that showed that dyslexics have poorer performance in tasks of phonological awareness, segmentation and manipulation of speech sounds.

This theory is criticized because it disregards the findings about non-linguistic deficits in dyslexic individuals. It does not emphasize which linguistic and non-linguistic risk factors, such as the auditory perceptual deficit, interact with phonological problems in the development of reading problems.

Allophonic Theory

This theory was developed based on evidence that dyslexic individuals present change on speech perception (Noordenbos & Serniclaes, 2015). The phonemic representation is the final product of a development process that has two important stages: the integration of universal allophonic characteristics into specific phonological characteristics of the language that happens when the individual is around one year old, and the combination of phonological characteristics into phonemic segments, which happens between 5 and 6 years old (Hoonhorst *et al.*, 2011).

According to the Allophonic Theory, dyslexics do not integrate the allophonic characteristics into phonemic characteristics during the speech perception development. Therefore, they perceive the speech in allophonic units rather than in phonemes. This is known as allophonic perception. This inability to integrate phonemic characteristics would not be secondary to the auditory perceptual deficit or alteration in phonological awareness. Rather, it would be caused by a failure in coupling phonetic predispositions during the perceptual development (Bogliotti *et al.*, 2008). According to Serniclaes, Heghe, Mousty, Carré and Sprenger-Charolles (2004), the Allophonic Theory differs from the Phonological Theory because the first advocates that changes on the speech sounds representation result from the failure in deactivating

the phonetic categories that are not relevant to the perception of phonemes present in the linguistic environment which are predisposed at birth. This way, the atypical perception of speech would be the direct cause of dyslexia, because the non-perception of phonemes specifically affects the mapping between graphemes and phonemes, damaging the understanding about the alphabetic principle. According to the Allophonic Theory, even the transparent alphabetic systems would become opaque for dyslexic individuals.

According to Serniclaes (2006), the deficit on categorical perception holds a core position among the many changes that have been associated with dyslexia. In this theory, the allophonic perception is the cause of the alteration in the phonological awareness because it affects the consistency of the mental representation of phonemes. This leads to an alteration in the reflection upon the misrepresented speech sounds. The deficit on short-term phonological memory is caused by the demand for higher memory load when we process the speech sounds coded as allophones rather than as phonemes. Just as the Phonological Theory, the Allophonic Theory is also subject to criticisms for disregarding the findings about non-linguistic deficits in dyslexic individuals, like the auditory perception deficit.

Auditory Deficit Theory

According to this theory, auditory deficit would be the direct cause of alteration during the phonological deficit development presented by dyslexic individuals and, in turn, of the difficulty in learning reading and writing skills. The phonological deficit would be a secondary deficit to a more elementary auditory deficit (Tallal *et al.*, 1993). Since the speech stimulus is an acoustic signal, alteration in auditory temporal processing may lead to difficulty in processing short elements, like the consonants that are characterized by fast formants transitions (Banai & Kraus, 2007; Ramus *et al.*, 2003). Alterations in the perception of short sounds and fast transitions of auditory stimuli would lead to important difficulties in the speech perception, with negative impacts on the construction of mental representations of the speech stimuli. The discrimination of phonemes for which the contrasting cues are auditory results impaired (Serniclaes *et al.*, 2001).

It is well documented that, underlying the reading difficulty presented by dyslexic individuals, there is a deficit on the linguistic system, more precisely on the phonological processing competences (Lieberman & Shankweiler, 1985; Peterson & Pennington, 2012; Ramus *et al.*, 2003). Learning reading and writing demands complex levels of phonological knowledge: it requires the proper representation of the smallest sound elements of the language (phonemes), good ability of reflecting on these elements, and knowledge that such sounds may be represented by different graphemes. The auditory experience is the typical sensorial route that allows children to acquire the phonological representations required to learn the skill of grapheme decoding (Morais, 2009).

Graphophonetic writing is the coding and decoding of graphic stimuli that represent sounds (phonemes). Learning to read demands the capacity of associating an auditory phonemic component with a graphic visual component. A

difficulty in handling the auditory phonemic component may be due to incipient sound stimulation that, in the event of auditory perception change, is not related to shortage of relevant stimuli in the environment, but to the difficulty or incapacity of processing the stimuli available. As such, one can assume that the deficit presented by the dyslexic individual may be not specific to the phonological processing, but secondary to a perceptual auditory deficit.

Many studies have shown deficit in phoneme discrimination by dyslexic individuals (Bogliotti *et al.*, 2008; Serniclaes *et al.*, 2001). According to the theory of auditory deficit the difficulty in perceiving and discriminating speech sounds results in difficulty to build mental representations that are important to the association between letters and sounds (Banai & Kraus, 2007; Birch & Belmont, 1964).

Many authors rebut this theory based on the evidence that not every dyslexic individual presents alterations in temporal processing. On the other hand, recurrent findings of alteration in auditory temporal processing in dyslexic individuals might mean different subtypes of dyslexia, one of which would be somehow associated to the change on the auditory temporal processing (Peterson & Pennington, 2012; Ramus *et al.*, 2003). Another possibility is that the alteration on the auditory temporal processing may have not been found in a portion of the sample of dyslexic individuals because it was overcome, and the occurrence in the early years of life may have had negative impacts on the development of the phonological representations (Boets, Wouters, Wieringen & Ghesquière, 2007).

Challenges for explanatory theories of dyslexia

According to Frost (1998), sometimes learning to read is mistakenly considered a visual skill, while in fact it is a linguistic process. Reading involves extracting linguistic information from the visual code that represents the speech. Ramus *et al.* (2003) carried out a study of 16 cases of dyslexic university students. They found that all cases presented phonological alteration. Auditory alteration was the most frequent alteration associated to phonological alteration in the studied sample, found in 10 out of the 16 cases.

The observation that not all dyslexic individuals present alterations in auditory processing may mean that there are different types of dyslexia, one of which associated to alteration in auditory processing, or just that deficits may have been overcome. The Phonological Theory believes that auditory perceptual alteration only co-exists with dyslexia and is not part of its genesis, neither interferes on its symptomatology. The Auditory Deficit Theory, in turn, says that auditory alteration is the cause of phonological deficit in dyslexia.

Landerl and Willburger (2010) dispute any causal relationship between dyslexia and changes on the temporal auditory processing. They argue that since not all individuals with temporal processing impairments have their reading and writing skills compromised, one cannot infer that changes on the temporal auditory processing are the cause of dyslexia. In order to test the Auditory Deficit Theory of dyslexia, the authors carried out a cross-sectional study of multiple cases with 40 children from 2nd to 4th grade of an Elementary School

I, who presented significant alteration in temporal processing. No consistent pattern of performance was observed in the tests used (reading words and pseudo-words, spelling, phonological awareness, rapid naming, attention, verbal and non-verbal IQ). Moreover, the correlations found were very weak, and 12 children performed well in reading skills, despite poor temporal processors. The authors concluded that problems related to temporal processing do not necessarily lead to impairment in reading and writing, but may be a marker of delay in the nervous system development. They suggest that difficulties of phonological origin specifically concern to a linguistic deficit that, in turn, is exclusively related to language processing.

In a systematic review of studies that verified the reading skills in individuals with altered auditory processing, Wit *et al.* (2016) pointed out that reading deficits in individuals with altered auditory processing were observed in all studies. According to Landerl and Willburger (2010) it can be interpreted that none of the alterations (in reading and auditory processing) are associated with each other, and both variables are related to a delay in the nervous system maturation. However, the consistent findings of reading deficits in individuals with history of chronic otitis media in childhood made us challenge this hypothesis. In individuals with history of otitis the reading difficulties could not be explained neither by a delay on the nervous system development, nor by cognitive deficits.

According to Balbani and Montovani (2003), the fluctuating nature of hearing loss in otitis media (which can alternate with periods of normal hearing) leads to an inconsistent sound stimulation of the central auditory nervous system, hindering the children from perceiving the speech sounds. Fluctuating sensitivity alterations cease with remission of the infectious process. However, despite the remission of otitis with advancing age, there are evidences that alteration in auditory processing remains. According to Zeng and Djalilian (2010), auditory deprivation in childhood, secondary to otitis, may have impacts on the development of auditory skills. This may cause an important change on auditory processing, mainly in temporal and speech processing. Balbani and Montovani (2003) emphasize that the inconsistency and alteration of the auditory system stimulation in the first three years of life, caused by chronic otitis, has long-lasting effects, compromising not only the acquisition of language in such a crucial period, but also the child's further academic learning.

For nine years Ruben (1999) monitored two groups of children with the same socioeconomic condition. One group was composed of 18 children who presented several episodes of otitis media in the first year of life, but presented normal hearing in the next eight years. The other group consisted of 12 children that had no chronic otitis media. The authors observed that the group with history of chronic otitis in the first year of life performed poorer than the control group in the eight measures that evaluated linguistic and language skills, like reading and writing. Although the otitis was evidenced only in the first year of life, the linguistic and language skills deficits were persistent, being observed in all stages, including at nine years old. These findings are consistent with those observed by Luotonen *et al.* (1998) in a population-based study with 1708 Finnish children.

The authors observed that when otitis media episodes were present in the first three years of life, these were associated with lower learning performance. However, the same was not true when the otitis occurred at older ages.

The finding that individuals with alteration on auditory processing present deficits in written language, and the observation that individuals with alteration in auditory processing resulting from chronic otitis in early childhood presented reading deficits, are evidences that auditory perception alteration interferes negatively in the reading and writing.

As aforementioned, the Phonological Theory postulates the specificity of the linguistic deficit in dyslexia. The phonological alteration would be the direct cause of dyslexia, while alterations in speech perception and auditory processing would only co-exist with dyslexia, neither interfering in its symptomatology nor being part of its genesis. The Allophonic Theory, in turn, postulates that the phonological change presented by dyslexic individuals would be caused by a deficit in the speech perception, characterized by an allophonic mode of perception, where there is insensitivity to the perception of phonemes. To the Auditory Deficit Theory changes on speech perception would be secondary to a more elementary alteration in the processing of acoustic stimuli. On the other hand, empirical data show weaknesses in these theories. Peterson and Pennington (2012) emphasize the relevance of research aimed to explain the still unclear nature of the phonological deficit, as well as works that better clarify which linguistic and non-linguistic risk factors – such as auditory perceptual deficit - interact with phonological deficit in the development of reading problems. They point out the perspective of more than one factor contributing to the development of dyslexia.

Auditory processing in dyslexic individuals

Tallal (1980) developed one of the first studies that evidence the presence of auditory perceptual change in dyslexic individuals. The author compared the performance of dyslexic children to that of typical readers in an experimental battery with non-verbal tests of discrimination and ordering of frequency, and also discrimination and ordering of duration. The studied group reported significantly lower performance in all auditory temporal tests. This leads to the conclusion that reading disorder is related to a perceptual auditory dysfunction.

Temporal processing is the auditory ability considered to be the most impaired of the auditory abilities in individuals with learning disabilities. It is involved in the perception of rapid changes, in the order of milliseconds, of the acoustic stimulus over time. It is of utmost importance because the acoustic information is somehow influenced by time, i.e., the sequencing of sound events, duration and intervals are aspects that integrate the properties of the stimuli and influence their perception. For the “speech” stimulus the temporal properties are the main linguistic contrast. Efficiency in temporal processing is necessary for the proper perception of speech (Rosen, 1992; Shinn, 2003). According to Froya and Pereira (2010) the integrity of auditory physiological mechanisms

plays a core role in the early acoustic processing, speech perception, learning and understanding of language. Therefore, it is a prerequisite to acquire reading and writing skills.

Cross-sectional studies on the incidence of alteration in auditory temporal processing in groups of dyslexic individuals found results ranging from 30% to 100% (Banai & Kraus, 2007; Ramus *et al.* 2003; Oliveira, 2011). This discrepancy may be partially due to the heterogeneity of instruments used to assess auditory temporal processing, and to different age groups studied. Longitudinal studies showed that the differences between the performance of dyslexic individuals and typical readers in tests evaluating auditory processing reduce as participants’ ages advance.

Hautus, Setchell, Waldie and Kirk (2003) have compared the performance of dyslexic individuals and typical readers of different age groups, in a task of detecting brief intervals of silence to evaluate the auditory temporal resolution skill. The authors found a significant difference in temporal resolution between the 6 to 9 age group. However, from age 10 on, the differences in the groups’ performances were not significant.

Boets, Vandermosten, Poelmans, Luts, Wouters and Ghesquière (2011) assessed the temporal auditory skills and speech perception of 62 children in pre-school age at three different moments: 5 years old (before literacy initiation); 6 years old (1st grade) and 8 years old (3rd grade, when they had been instructed on reading and writing for two years and two months). Half of the participants were recruited because of the increased risk of presenting problems with reading and writing, based on their family’s history. Even before starting the formal literacy process, participants later diagnosed as dyslexics (in the 3rd grade) already presented sharp difficulty in the auditory temporal processing, with significant differences in relation to participants that were not later diagnosed as dyslexic.

Fischer and Hartnegg (2004) evaluated the auditory temporal processing of groups of dyslexic individuals and typical readers of 7 to 19 years old. They found strong interaction between age and performance in the skill of auditory temporal resolution in both groups. However, the interaction between age and performance in temporal resolution for the group of dyslexic individuals was stronger than in the group of typical readers. The difference between typical readers and dyslexic individuals in temporal resolution was very expressive at the age of 7, sharply decreasing at 9 years old, becoming not significant from 12 years on.

Prestes (2016) investigated auditory skills of resolution and temporal ordering among dyslexic individuals and how these variables were related to reading, writing skills and phonological awareness. The dyslexic individuals presented deficits in the auditory skills assessed if compared to typical readers in the same age group. The lower performance in the skills of resolution and auditory temporal ordering was related to greater occurrence of a specific type of spelling error, named voiced/voiceless interchange. The author also observed that the greater occurrence of other spelling errors and lower performance in reading was associated to lower performance in phonological awareness and auditory temporal ordering. Based on a hierarchic regression analysis, the auditory temporal ordering helped explaining the read-

ing performance even considering the contributions by the phonological awareness.

Speech perception in dyslexic individuals

Dyslexic individuals present deficit in phonemic discrimination and categorical perception of speech sounds (Boets *et al.* 2011; Bogliotti *et al.*, 2008; Noordenbos & Serniclaes, 2015; Prestes, 2016; Serniclaes *et al.*, 2004; Vandermosten *et al.*, 2010). Categorical perception can be defined (Elangovan & Stuart, 2008) as abrupt change from the perception of a phonemic category to another in a given time along a continuum. To Liberman, Harris, Hoffman and Griffith (1957) categorical perception is the degree in which the acoustic differences between variants of the same phoneme are less perceivable than the differences of the same acoustic magnitude between two different phonemes.

According to Liberman *et al.* (1957), speech perception takes place in a categorical way at some level, i.e., part of the acoustic information of the speech stimuli is ignored in favor of discreet categorical labels. Therefore, the categorical perception is adaptive since it enables rapid classification of transient events, like the succession of phonemes in speech, by allowing neglect of irrelevant stimulus information (Bogliotti *et al.*, 2008). To Hoonhorst *et al.* (2011), through the transformation of sensations into discreet representations, categorical perception is an economic way of processing the information flow present in the environment.

Pooling stimuli in cognitively efficient categories to facilitate storage and retrieval of information is typical to human perceptual systems. We ignore irrelevant variations to focus on what defines an object in relation to others (Tristão & Feitosa, 2003). The authors affirm that categorical perception is a phenomenon of perceptual constancy or standardization. Its complex mechanism enables an individual to consistently recognize phonemes, despite the huge variability in crucial acoustic parameters.

Different studies (Serniclaes *et al.*, 2001; Serniclaes *et al.*, 2004) suggest that dyslexic children are less categorical than typical readers in how they perceive phonetic contrasts. The dyslexic individuals' discrimination between phonemes of different phonetic categories is impaired, and they are more "skilled" to discriminate acoustic variants of the same phoneme. That means to say that distinctions between categories are less well defined and the inner structure of the categories are less coherent.

Several studies aimed to investigate the change in speech categorical perception presented by dyslexic individuals could be just a consequence of the reading level (Boets *et al.*, 2011; Bogliotti *et al.*, 2008). To that, dyslexic individuals were compared to paired control for reading level. Studies showed that deficit in speech perception was also found when dyslexic individuals were compared to individuals paired for reading level. Moreover, longitudinal studies have observed deficit in the categorical perception of speech before starting literacy among individuals who were later diagnosed as dyslexic (Boets *et al.*, 2011).

There are two main theories on the deficit of categorical perception presented by dyslexic individuals. The first

assigns the cause of the perceptual deficit to the change on auditory temporal processing, based on the dyslexia's Auditory Deficit Theory. In this light, the grounds of the specific reading disorder would be a deficit in a more elementary level of the auditory perception (auditory temporal processing) that jeopardizes the speech perception and, in turn, the construction of phonological representations (Vandermosten *et al.*, 2010). The second one is the Allophonic Theory that explains the deficit in the categorical perception of speech as an unconventional form of speech perception, based on the allophonic perception. In other words, dyslexic individuals would perceive the speech based on the use of allophones rather than phonemes, as it usually happens with typical readers. Allophones are contextual variations (phonetic manifestations) of the phonemes. The phonological representations do not include allophones, being based only on contrasting properties (Cristófaró-Silva, 2002). According to this theory, the atypical way of perceiving the speech would be the direct cause of dyslexia.

The categorical perception deficit reflects high capacity of discriminating non-functional differences between stimuli. These differences are of allophonic nature as they correspond to distinctions that are mere contextual phonemic variants in the language of interest, being phonemic in other languages (Bogliotti *et al.*, 2008). This high discriminability is also observed among children in the pre-lingual stage. However, this form of perception is usually reorganized, mainly in the first year of life, becoming specialized in the language to which the speaker is exposed.

Babies are born with ability to distinguish universal phonetic contrasts that are independent of maternal (or native) language, but cannot make all the phonetic distinctions used in adult language. Eimas, Siqueland, Jusczyk and Vigorito (1971) have analyzed the ability of discrimination between stimuli of a *continuum* /ba-pa/ based on the suction pattern of babies of 1 to 4 months of age. They found that babies differentiated stimuli like adults. Consistently, Eimas (1975) observed that babies from different maternal languages discriminated perceptual continua in similar ways. The researcher understands that the perceptual organization observed in babies is part of their biological composition, being a characteristic inherent to the auditory sensitivity. Phonetic frontiers are anchored in psychoacoustic thresholds.

This capacity of distinguishing phonetic contrasts can be either improved or neutralized, depending on the relevance of contrasts in the listener's linguistic environment. As age advances (and linguistic experience increases), speech perception takes on a specialized way in the contrasts found in the linguistic environment to which the baby is exposed. Predispositions to distinguish all the phonemic categories in the world are typically deactivated as age advances, and the specialized perception in maternal language is usually completed around the age of 9 (Hoonhorst *et al.*, 2011).

Babies in pre-lingual phase are considered to be universal perceivers, i.e., they perceive the categories that define the phonetic classes in all the world's languages (Kuhl, 2004; Tristão & Feitosa, 2003). According to Kuhl (2004), the most basic auditory skills are related to the phonetic frontier. This is not a casual association, but a demonstration that babies perceive a natural discontinuity in a point of the *continuum*.

Phonemic frontiers change as age (and exposure to the linguistic environment) develops, moving from predisposed categories governed by automatic processes to a context-sensitive speech perception that, as such, is governed by conscious processes (Serniclaes, 2011; Serniclaes *et al.*, 2004).

According to the Allophonic Perception Theory the dyslexic individuals present a persistent atypical form of perception. Noordenbos and Serniclaes (2015) speculate that the reorganization of phonological representation does not happen to the same extension in dyslexic individuals for genetic reasons and the allophonic speech perception is one of the likely causes of dyslexia. For the authors, the allophonic perception does not allow the correct establishment of graphophonetic relations even in perfectly transparent alphabetical systems, causing an important disturbance of the written language development. According to Bogliotti *et al.* (2008) the permanence of the discrimination of phonetic characteristics that are irrelevant to the maternal language's phonology is likely to be a consequence of the atypical perceptual development in early childhood.

The perception of allophonic variants during the beginning of the acquisition process of reading and writing has important implications because it shows the weakness, or even the complete absence of representations at phonemes level (Serniclaes *et al.*, 2004). This absence of phonemic representations would undermine the understanding of the regularity of biunivocal relationships, interfering in the establishment of grapheme-phoneme relations, even in the most transparent orthographic systems. The authors emphasized that the harmful effect of allophonic perception on reading and writing does not necessarily impair the understanding of speech, because it does not fundamentally involve phonemes as units of analysis. The access to the mental lexicon is conceivable based on allophonic representations, although these are more demanding since they require processing a huge amount of redundant information.

To the Auditory Deficit Theory, the speech perception deficit presented by dyslexic individuals is secondary to a more fundamental deficit in the auditory processing. This proposition is anchored in evidences that categorical perception deficit is not exclusive to linguistic stimuli (Boets *et al.*, 2011; Vandermosten *et al.*, 2010).

To check if the auditory processing deficit presented by dyslexic individuals is specific to the speech perception or can be reduced to a more basic and general change of acoustic processing, Vandermosten *et al.* (2010) analyzed the perception of verbal and non-verbal stimuli in a sample of 31 dyslexic adults and 31 typical readers. A task of identification of the *continuum* /ba-da/ and a task of identification of non-verbal stimuli with spectral complexity similar to the *continuum* /ba-da/ were performed. The authors found that the auditory perceptual deficit presented by dyslexic adults was not specific to the processing of speech stimuli, considering that it was also observed in the perception of non-verbal stimuli. This provided evidences that corroborate with the hypothesis that there is a more fundamental change on auditory processing underlying the deficit of representation of speech sounds presented by the dyslexic individuals.

The Contribution of Evidences on Changes in Auditory Processing and in the Speech Perception in Dyslexic Individuals for Explanatory Theories of Dyslexia

The findings about alterations in the auditory processing and speech perception and their relationships with reading, writing and phonological awareness have different interpretations depending on the theoretical assumptions, as further analyzed.

The phonological theory considers the phonological deficit as a direct and specific cause of dyslexia. Although widely accepted, this theory is criticized because it disregards the consistent findings of perceptual alterations like the deficit in auditory processing among dyslexic individuals. The auditory perceptual deficit would then just co-exist with dyslexia, and would neither be part of its genesis nor interfere on the symptomatology.

There are some reasons that lead us to question whether it would be possible for a change in auditory processing not to interfere with the construction of phonological representations, mainly if that change happens during the critical period for language development, i.e., in the early years of life. One likely reason is the large body of evidence of deficits in oral and written language among individuals presenting changes in auditory processing. Among these evidences, we could highlight the longitudinal studies with children presenting auditory alteration in early childhood resulting from chronic otitis (for example, Ruben, 1999).

Inconsistency and alterations in stimulation of the peripheral auditory system in the first three years of life, due to chronic otitis, lead to an equally inconsistent sound stimulation to the central auditory nervous system, compromising the development of auditory skills and the construction of phonological representations (Luotonen *et al.*, 1998). Despite infection remission still in early childhood, changes in the auditory processing remain and have harmful and persistent effects on phonological representations and in the acquisition of reading and writing skills. This evidence stands out because the change in auditory processing is of sensorial origin, and cannot be interpreted as resulting from delayed maturation of the nervous system. Therefore, reading and writing difficulties would be directly related to perceptual difficulties in processing acoustic stimuli.

Alterations in auditory processing and phonological representation are related because the auditory experience is the typical sensorial route that allows children to acquire the phonological representations required to learn reading and writing (Morais, 2009). There are evidences that musical training (which does not involve linguist stimuli, but demands considerable temporal processing) promotes not only the improvement of auditory skills, but also of the linguistic domain (Eugênio, Escalda & Lemos, 2012). Therefore, the construction of these representations may be impaired by an inability regarding the auditory processing of acoustic cue relevant to differentiate the phonemes.

Additionally to the change in temporal auditory processing, there is increasing evidence of change on the speech perception in groups of dyslexic individuals, mainly in the tasks of phonemic identification and discrimination, as well as in the identification and discrimination of phonemes that

are only differentiated by the sonority trait (Noordenbos & Serniclaes, 2015). The discrimination during the production of speech of these pairs of phonemes cannot resort to visual cues, since these pairs are visually similar in topography of articulation. Considering this, difficulties in the graphic coding and decoding of voiced/voiceless phonemes could be related to a difficulty in the auditory perception of relevant cues to discriminate these phonemes.

According to Russo & Behlau (1993), the most relevant factor to discriminate the sonority trait in plosive phonemes is the voice onset time (VOT). There is evidence that the perception of temporal cues that define the phonemes as voiceless or voiced depend on a well-developed skill of auditory temporal resolution (Elangovan & Stuart, 2008). This way, we could hypothesize that voiceless/voiced interchanges are a manifestation of alteration in auditory temporal processing. This hypothesis is strengthened by evidence that this kind of misspelling is more frequent in oralized deaf and dyslexic individuals (Zoubinetzky *et al.*, 2014), for whom the alteration in auditory temporal processing is well documented.

According to the Allophonic Theory, reading and writing manifestations in dyslexia profile, like the voiceless/voiced exchanges, would result from an alteration in the development of the speech perception resulting from a failure in integrating allophonic characteristics into phonemic characteristics. This way, the dyslexic individuals would perceive the speech in allophonic units rather than in phonemes; this is the so-called allophonic perception. This non-perception of phonemes would impair understanding the alphabet principle.

According to Serniclaes *et al.* (2004), the Allophonic Theory differs from the Phonological Theory because the first advocates that alterations in the representation of speech sounds result from the failure in deactivating the phonetic categories that are not relevant to the perception of phonemes present in the linguistic environment, which are given at birth. In opposition to the Allophonic Theory, the Auditory Deficit Theory postulates that difficulty in processing the speech stimuli is related to insensitivity to detect acoustic cues that are relevant to differentiations more complex than the distinguishing between categories given at birth.

Babies are born with capacity of distinguishing universal phonetic contrasts that are not dependent on the maternal language, but cannot make all the phonetic distinctions used in adult language. This perceptual organization observed in babies is a trait inherent to auditory sensitivity, and is anchored in the psychoacoustic thresholds (the phonetic boundaries). With the linguistic experience and development of auditory perceptual skills, babies start perceiving the phonemic contrasts present in their maternal language. To that, the perceptual skill must be refined, considering that the perception of phonemic boundaries acquired through the linguistic experience demands a refined analysis of the acoustic stimulus.

According to Serniclaes (2011), the acquisition of the phonemic boundary demands the temporal processing of the order of two events and is intrinsically more complex than that of universal boundaries. According to the Allophonic Theory, the failure in coupling the boundaries is the cause of dyslexia, rather than being secondary to a change in the processing of acoustic stimuli, or to a phonological processing deficit.

Conclusions

This study aimed to discuss the Dyslexia's Explanatory Theories (Phonological, Allophonic and Auditory Deficit) based on findings about alterations in auditory processing and speech perception among dyslexic individuals. Understanding the picture that underlies this disorder, which is highly prevalent, is of utmost relevance because it allows early identification of individuals with indicators of risk factors for dyslexia. Moreover, it assists the diagnosis process and planning of early intervention strategies, based on scientific evidences.

We believe that a very important difficulty in the auditory processing of speech sounds can impair the construction of phonological representations, leading to difficulty to establish the graphophonemic relation. On the other hand, we question if the auditory perceptual alteration, *per se*, could harm the phonological skills to the point of giving rise to a picture of dyslexia. In this scope, the findings of changes of the auditory processing among individuals that were not classified as dyslexics in Prestes' (2016) study are very informative because she observed that alteration in auditory processing *per se* is not enough to cause dyslexia.

An alteration in auditory processing can damage the construction of phonological representations. The reflection on speech sounds, however, based on little consistent elements would not necessarily impair the ability to mentally operate these elements, like dividing syllables and excluding syllables from words. The deficit in phonological skills presented by dyslexic individuals extrapolates the metal representation of the speech sounds, compromising other phonological abilities like the rapid naming skill. To impair cognitive skills, the inconsistency in phonological representation should be big enough to compromise the differentiation of phonemes, which would probably be strongly manifested in the speech. Despite the evidences that dyslexic individuals presenting alterations in auditory temporal processing also present compromised oral language (Tallal, 1980), dyslexia is more likely to be multifactorial, including a cognitive deficit related to the ability of metalinguistic reflection, and a deficit in auditory temporal processing that contributes to worsening the symptomatology.

The metalinguistic reflection skill (as cognitive skill) may be the tool used by typical readers presenting change on the auditory temporal processing to the good development of phonological representations. In other words, individuals with well-developed linguistic skills may resort to these skills to overcome potential harmful effects that alterations in auditory processing may have on the perception of speech and construction of phonological representations.

The individuals with auditory perceptual deficits and phonological skills deficits present impaired construction of mental representations of the speech sounds that, in turn, maximizes the difficulty of reflection over these poorly-represented sounds. The deficit in acoustic stimuli processing, associated to a linguistic cognitive deficit, may damage the metalinguistic reflection ability due to the need for elements to consolidate it, which leads to the picture of dyslexia.

Neither the Phonological Theory nor the Auditory Deficit Theory contemplates the integration of deficits into the phonological and auditory processing as different factors

interacting in the dyslexia genesis. The Phonological Theory objects to the influence of auditory perceptual alterations on the dyslexia's symptomatology, and the Auditory Deficit Theory postulates that phonological processing deficit is a secondary one, directly caused by the auditory perceptual deficit.

The Allophonic Theory understands that dyslexia is caused by a speech perception deficit. In this sense, its theoretical framework is also related to the Auditory Deficit Theory because both assume that the change on speech perception would lead to a deficit in the construction of phonological representations and skills. However, these theories are different regarding the concepts about the cause of the speech perception deficit. According to the Auditory Deficit Theory, the cause of dyslexia is the most elementary deficit in the processing of acoustic stimuli. To the Allophonic Theory, it is a failure in coupling phonetic categories given at birth that impairs perceiving the phonemes.

Therefore, although the three theories contribute towards understanding dyslexia, they pose problems because they advocate for the determinism of a single deficit and the dissociation between the many deficits found in dyslexic individuals. Although the Auditory Deficit and Allophonic Perception theories comprise the deficit in phonological processing (and thus do not incur in the error of dissociating deficits), both consider it secondary to a more elementary deficit. Neither the difficulty in auditory processing nor the failure in coupling the predisposed phonetic categories can fully explain the phonological difficulties presented by the dyslexic individuals.

We believe that dyslexia is a multifactorial disorder, with a wide range of associated behavioral symptoms that cannot be explained by one single deficit. The deficit presented by dyslexic individuals is neither uniquely linguistic, as advocated by the Phonologic Theory, nor directly caused by the auditory perceptual change as postulated by the Auditory Deficit Theory. Both factors interact and are inseparable to explain the symptomatology observed in reading and writing disorders. That points out the need for efforts towards building an Integrative Theory to explain dyslexia.

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