Auditory Temporal Processing Deficits in Developmental Dyslexia

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Abstract

Developmental dyslexia refers to a learning disability wherein individuals with normal intelligence and adequate school education still fail to acquire age-appropriate reading skills, and the nature of its underlying deficit has long been a focal point of debate among researchers. Extensive research has demonstrated that individuals with dyslexia frequently exhibit impairments in auditory temporal processing. At the behavioral level, dyslexics show difficulty in discriminating the order of rapidly and sequentially presented stimuli as well as the dynamic temporal characteristics of the stimuli themselves. At the neural level, dyslexics elicit weaker mismatch negativity and display abnormal neural synchronous processing. These impairments are present in both speech and non-speech stimulus processing, indicating that auditory temporal processing deficits are not specific to speech processing. Future research must address the following questions: 1) In which temporal windows do auditory temporal processing deficits in dyslexia occur, and how do they change with age; 2) What is the temporal course at the neural level of auditory temporal processing deficits in dyslexia; 3) Are auditory temporal processing deficits a core deficit of dyslexia.

Full Text

Auditory Temporal Processing Deficits in Developmental Dyslexia

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Abstract: Developmental dyslexia is a learning disability in which individuals fail to acquire age-appropriate reading skills despite normal intelligence and adequate educational opportunity, and the nature of its underlying deficits has long been a subject of debate. A substantial body of research has demonstrated that individuals with dyslexia consistently exhibit impaired auditory temporal processing. At the behavioral level, dyslexics struggle to discriminate the temporal order of rapidly and successively presented stimuli as well as the dynamic temporal characteristics of the stimuli themselves. At the neural level, dyslexics show weaker mismatch negativity (MMN) responses and abnormal neural synchronization. These impairments are observed in the processing of both speech and non-speech stimuli, indicating that auditory temporal processing deficits are not specific to speech processing. Future research must address three key questions: (1) In which temporal windows do auditory temporal processing deficits in dyslexia occur, and how do they change with age? (2) What is the neural time course of auditory temporal processing deficits in dyslexia? (3) Are auditory temporal processing deficits a core deficit in dyslexia?

Keywords: developmental dyslexia, auditory temporal processing, temporal order, dynamic temporal feature, mismatch, neural synchronization

1 Introduction

Developmental dyslexia (DD) is a neurological disorder characterized by a specific deficit in fluent reading acquisition despite normal intelligence, adequate educational and sociocultural opportunities, and the absence of visual or auditory impairments (Casini et al., 2018). Phonological deficits are widely regarded as the core impairment in alphabetic dyslexia (Casini et al., 2018; Goswami, 2015; Snowling, 2001). Researchers have argued that deficits in the representation, storage, and retrieval of phonological information impair grapheme-phoneme conversion processes, thereby compromising reading ability (Snowling, 2001). However, other researchers contend that phonological deficits are merely a surface manifestation of more fundamental general sensory deficits (Lovegrove et al., 1980). Temporal processing (TP) is a cognitive-neural mechanism that encodes, decodes, and evaluates temporal structures (duration, order, speed, or regularity of events) during cognitive operations (Kotz & Schwartze, 2010), responsible for low-level processing of stimulus temporal features, including perceiving stimulus duration, rapid changes, and sequence across different sensory modalities (Grondin, 2010). Researchers propose that phonological skill deficits in dyslexia may stem from underlying auditory temporal processing deficits (Meng et al., 2005). Rise time is a critical event in speech signals that helps segment acoustic signals into temporal windows, thereby providing effective cues for speech perception (Goswami, 2011; Goswami & Leong, 2013; Hämäläinen et al., 2012). Neural networks utilize cues provided by rise time to reset and calibrate neural activity, synchronizing it with speech signals (Gross et al., 2013). Consequently, abnormal neural synchronization to rise time may constitute the neural basis of phonological deficits in developmental dyslexia (Goswami, 2011, 2018, 2019).

Additionally, individuals can order sounds by perceiving frequency and amplitude changes (Stein, 2018), and mismatch negativity (MMN) effectively reflects the ability to detect changes in auditory information, making it an excellent tool for revealing auditory temporal processing deficits in dyslexia.

Numerous behavioral and neuroscience studies have demonstrated that alphabetic dyslexics exhibit auditory temporal processing deficits, including lower accuracy in judging the order of rapidly changing stimuli (Fostick et al., 2012, 2014; Tallal, 1980), reduced MMN elicitation by novel auditory temporal stimuli (Corbera et al., 2006; Meng et al., 2005; Schulte-Körne et al., 1999; van Zuijen et al., 2012), and weaker rise time discrimination and neural oscillation synchronization abilities (Goswami et al., 2010, 2011; Power et al., 2012, 2013, 2016; van Hirtum et al., 2019). Similarly, Chinese dyslexics also show abnormal processing of auditory temporal stimuli (e.g., Chung et al., 2008; Liu et al., 2019; Wang & Yang, 2018), reflecting cross-linguistic consistency in auditory temporal processing deficits. Such deficits not only interfere with phonological processing, making it difficult to manipulate grapheme-phoneme correspondences (Booth et al., 2000), but also disrupt attention allocation and dynamic switching, preventing critical phonological information from being attended to and captured in a timely manner, thereby reducing reading efficiency (Goswami, 2011). Therefore, auditory temporal processing deficits may be a causal factor in developmental dyslexia. Intervention studies have confirmed that auditory rhythm training (Bhide et al., 2013; Flaugnacco et al., 2015) and auditory temporal perception training (Zhang et al., 2018; Wang et al., 2019; Zhang et al., 2018) can significantly improve reading performance in dyslexics, suggesting a causal relationship between auditory temporal processing deficits and dyslexia.

This paper systematically reviews research on auditory temporal processing deficits in developmental dyslexia, examining both behavioral and neural characteristics of these deficits, and concludes with future research directions.

2.1 Temporal Order Processing Deficits

Tallal (1980) defined temporal processing as the processing of rapidly presented stimuli, and research on rapid auditory temporal processing in alphabetic dyslexia began with Tallal. Over nearly four decades, researchers have predominantly employed temporal order judgment (TOJ) paradigms, in which participants judge the order of rapidly presented stimuli (Chung et al., 2008). Using non-speech auditory stimuli, Tallal required participants to judge stimulus presentation order and found that dyslexic children struggled to discriminate the order of tones presented within short intervals (8-305 ms), though this deficit disappeared when intervals exceeded 305 ms. Tallal also found that temporal processing of non-speech tones significantly correlated with phonological coding, word identification, and spelling. Nittrouer (1999) challenged Tallal' s findings by using more discriminable tones (800 Hz and 1200 Hz) for 8-year-old children. Results showed no significant differences between dyslexic and typical children regardless of interval length, leading to the suggestion that previous stimuli may have been insufficiently discriminable, accounting for the observed deficits (Nittrouer, 1999). Subsequently, Rey et al. (2002) required participants to judge the order of consonants in nonsense syllables (e.g., "aspa") while manipulating consonant duration. Dyslexic children performed significantly worse than controls when stimulus duration was short (140 ms), but reached normal performance levels when duration increased (280 ms). Correlational analyses revealed that dyslexic children' s auditory TOJ performance significantly correlated with phonological awareness and nonword spelling, leading researchers to conclude that perceiving two successive consonants is more difficult than perceiving tones, and that Nittrouer' s task may have been too simple (Rey et al., 2002).

In Chinese studies, Meng et al. (2005) tested typically developing fifth-grade children in mainland China, requiring them to judge the order of two tones (800 Hz and 2000 Hz) presented with 50–100 ms intervals. Results showed that TOJ performance significantly correlated with multiple phonological and reading measures, and after controlling for phonological awareness, TOJ performance consistently explained variance in reading fluency. These findings indicate that auditory temporal processing plays an important role in Chinese children's reading development (Meng et al., 2005). Subsequent studies have confirmed auditory temporal processing deficits in Chinese dyslexic children (e.g., Chung et al., 2008; Liu et al., 2019; Wang & Yang, 2018; Wang et al., 2019). Chung et al. (2008) recruited Hong Kong primary school children to judge the order of high-frequency (500 Hz) and low-frequency (250 Hz) sounds across different intervals (8–305 ms). Results showed that dyslexic children (Mage = 8.90) had significantly lower accuracy than age-matched controls (Mage = 8.91) across all interval conditions, but did not differ from reading-level-matched controls (Mage = 8.30), suggesting that Chinese dyslexic children may simply show developmental delay in auditory temporal processing (Chung et al., 2008). Similarly, Wang and Yang (2018) tested Taiwanese primary school children in grades 1-6 (Mage: 7.76-11.68) on an auditory TOJ task and found that dyslexic children in grades 1–2 had significantly lower accuracy than same-grade typical children, but this difference disappeared from grade 3 onward. However, a recent study with predominantly grades 3–6 children (81% of the sample) found that dyslexic children (Mage = 9.82) performed significantly worse than typical children (Mage = 9.66) on the TOJ task, and this difference remained after controlling for age and nonverbal intelligence (Liu et al., 2019). Additionally, research has documented auditory temporal processing deficits in dyslexic adults (e.g., Fostick et al., 2012, 2014). Fostick et al. (2012) found that dyslexic adults performed worse than typical readers on auditory temporal processing tasks (TOJ and temporal gap detection) even after controlling for working memory, but showed no differences in intensity perception tasks. These results indicate that adult dyslexics exhibit specific deficits when auditory discrimination relies on temporal operations, which cannot be attributed to general perceptual deficits or working memory impairments (Fostick et al., 2012). Subsequently, Fostick et al. (2014) used a binaural TOJ task to train dyslexic adults, presenting pairs of tones (identical in frequency and intensity) to both ears at different intervals (5–240 ms) and requiring participants to judge which ear received the tone first. After five days of training, both dyslexic and typical adults showed significant improvements in pseudoword reading and phonological awareness, while untrained control groups showed no significant changes (Fostick et al., 2014). These non-speech findings suggest that auditory temporal processing deficits in developmental dyslexia represent a more general sensory deficit rather than one specific to speech stimuli.

However, dyslexic temporal order processing deficits are not limited to rapidly presented stimuli. Cestnick and Jerger (2000) found that dyslexic children showed significantly lower accuracy than typical children on auditory TOJ tasks regardless of presentation speed (rapid: 8–305 ms; slow: 428 ms). A subsequent large-scale longitudinal study (Share et al., 2002) found that children diagnosed with dyslexia in second grade had shown significantly lower accuracy than age-matched typical children on long-interval TOJ tasks (428 ms) three years earlier, with marginally significant differences on short-interval tasks (8–305 ms, $p = 0.07$). Researchers suggested that Tallal' s use of extensive training and test trials may have allowed participants to gain experience from additional practice, making long-interval perception easier and thereby attenuating differences between dyslexic and typical children (Share et al., 2002). Therefore, dyslexic auditory temporal processing deficits do not appear limited to brief temporal windows, though whether these deficits exist across broad temporal domains or only in specific windows (e.g., those corresponding to linguistic units) requires further investigation.

2.2 Dynamic Temporal Feature Processing Deficits

Studdert-Kennedy and Mody (1995) noted that while stimulus identification is a prerequisite for temporal order judgment, temporal processing only occurs when stimulus features change dynamically over time. Poor performance on auditory TOJ tasks by dyslexics may reflect unidentified discrimination deficits rather than genuine auditory temporal order processing deficits (Studdert-Kennedy & Mody, 1995). Consequently, some researchers have examined dyslexic auditory temporal processing from the perspective of the auditory system' s encoding of sound dynamics (e.g., amplitude rise time, frequency modulation detection). Witton et al. (1998) presented adult participants with pairs of pure tones and frequency-modulated (FM) tones in random order, requiring them to report which tone was FM. Dyslexic adults showed higher (worse) FM detection thresholds at modulation rates of 2 Hz and 40 Hz, but no significant differences from controls at 240 Hz. The researchers noted that perceiving 2 Hz and 40 Hz FM tones relies more on temporal cues, whereas perceiving 240 Hz FM tones relies on spectral cues, suggesting that dyslexic adults are insensitive to auditory stimuli with dynamic temporal properties (Witton et al., 1998). Notably, dyslexics showed processing deficits at both low (2 Hz) and high (40 Hz) modulation rates, indirectly suggesting that dyslexic auditory temporal processing deficits exist across broader temporal domains.

Rise time is a critical event in speech signals that reflects amplitude modulation patterns, which help segment acoustic signals (e.g., syllables) into temporal windows (Goswami, 2018), providing effective cues for speech perception (Goswami, 2011; Goswami & Leong, 2013; Hämäläinen et al., 2012). Goswami et al. (2010) conducted a longitudinal study in southern England and found that dyslexic children showed significantly higher (worse) discrimination thresholds for amplitude rise time (non-speech tones) compared to both age-matched and younger reading-level-matched controls (Goswami et al., 2010). Subsequently, Goswami et al. (2011) used the same rise time discrimination test to investigate general sensory deficits in dyslexic children from England, Spain, and Taiwan. Results showed that dyslexic children from all three regions had significantly higher rise time discrimination thresholds than age-matched controls, and that rise time thresholds significantly predicted phonological awareness and reading performance, indicating that impaired rise time discrimination is a universal sensory deficit in developmental dyslexia with cross-linguistic consistency (Goswami et al., 2011). Furthermore, studies of preschool children at familial risk for dyslexia have found similar impairments in rise time discrimination, with high-risk children showing significantly higher thresholds than low-risk children, and rise time thresholds significantly correlating with syllable awareness: lower thresholds predicted higher syllable awareness scores (Law et al., 2017). Recent research (Kalashnikova et al., 2018, 2019) has examined the relationship between infants' sensitivity to rise time and their later language abilities. At-risk 10-month-old infants showed significantly poorer sensitivity to amplitude rise time than control infants (Kalashnikova et al., 2018). Control 7-month-old infants had significantly higher rise time discrimination thresholds than 10-month-olds (sensitivity increased with age), but this age-related improvement was absent in the at-risk group. Moreover, infant rise time discrimination thresholds predicted vocabulary levels at age 3. The researchers concluded that infants' sensitivity to rise time is an important developmental marker for later oral and written language impairments (Kalashnikova et al., 2019). In summary, individuals with developmental dyslexia exhibit auditory temporal processing deficits that exist across languages and developmental stages, representing a fundamental deficit of the disorder.

3.1 Abnormal Mismatch Negativity Responses

At the neural level, MMN elicited by novel auditory temporal stimuli can reflect auditory temporal processing deficits in developmental dyslexia. Schulte-Körne et al. (1999) presented participants with four consecutive non-speech pure tones of different durations while they watched a silent film; standard stimuli comprised 85% of trials and deviant stimuli 15%. Results showed that dyslexic adults exhibited significantly smaller MMN amplitudes than typical adults in the 225-600 ms time window, indicating deficits in processing rapid temporal information (Schulte-Körne et al., 1999). Meng et al. (2005) tested Chinese dyslexic children using a passive oddball paradigm and found that dyslexic children showed smaller mean MMN amplitudes in response to novel temporal interval stimuli than typical children (Meng et al., 2005). Corbera et al. (2006) used a similar passive task to examine neural responses to novel auditory stimuli in dyslexic children. In the frequency condition, standard stimuli were 500 Hz (80%) and deviants 550 Hz; in the duration condition, standard stimuli were 100 ms (80%) and deviants 33 ms. Results showed that dyslexic children had significantly larger mean MMN amplitudes and longer latencies than age-matched typical children in the duration condition, but no significant differences in the frequency condition, suggesting that dyslexic auditory processing deficits stem from impaired discrimination of temporal cues (Corbera et al., 2006). Van Zuijen et al. (2012) conducted a longitudinal study of infants at familial risk for dyslexia, recording EEG during a passive oddball paradigm at 17 months of age. At-risk infants failed to show significant mismatch responses (MMR) to novel temporal interval stimuli, whereas control infants exhibited significant MMR. Follow-up behavioral measures revealed that frontal-central MMR amplitude at 17 months significantly correlated with language comprehension at 53 months and with real-word and pseudoword reading fluency at the end of second grade. These findings demonstrate that MMN and MMR can serve as neural markers of developmental dyslexia across languages and ages. However, these studies have only examined the neural mechanisms underlying discrimination of novel auditory temporal stimuli; the neural mechanisms of more general auditory temporal processing and their temporal dynamics remain to be investigated.

3.2 Abnormal Neural Oscillation Synchronization

In addition to MMN, neural oscillation synchronization can also reflect auditory temporal processing deficits in developmental dyslexia. The brain can "sample" information from speech streams at different rates, enabling neural oscillations in different frequency bands to synchronize and phase-lock with similar frequency components in the input signal (Goswami, 2019; Power et al., 2012). Neural phase-locking is crucial for temporal encoding and parsing of speech signals, particularly in the theta band (consistent with syllabic modulation rates) and gamma band (consistent with phonemic modulation rates), and is essential for language acquisition and development. Methods for assessing neural oscillation synchronization can help explore developmental learning difficulties involving temporal sampling deficits, such as dyslexia (Power et al., 2012). Power et al. (2013) used a rhythmic synchronization task with EEG recording to examine neural synchronization to rhythmic speech in dyslexic children. The auditory rhythmic speech consisted of repeated syllables "ba" at 2 Hz (delta band). During syllable repetition, occasional frequency-violation syllables occurred, to which participants responded with a button press (though responses were not analyzed). Results showed abnormal delta-band neural oscillation synchronization in dyslexic children, whose neural responses to delta-band modulated information were delayed by an average of 12.8 ms compared to typical readers, indicating differences in preferred phase. Preferred phase reflects the time point in an oscillation cycle (from activation to inhibition) when most neurons fire; if the oscillatory peak representing maximal neuronal excitability occurs when the speech signal carries minimal information (e.g., neural oscillations are out-of-phase with amplitude modulation information), speech perception will be adversely affected (Goswami, 2019). Thus, the auditory temporal reference frame for speech processing is abnormal in dyslexic children, manifested as synchronization of low-frequency oscillations to different phases of speech input, which affects the quality of phonological encoding and may underlie impaired phonological representations (Power et al., 2013). Subsequently, Power et al. (2016) selected participants from a previous longitudinal behavioral study (Goswami et al., 2013) and required them to repeat semantically unpredictable but grammatically correct sentences (e.g., "Arcs blew their cough") and judge whether stress patterns were identical in two pronunciations of the same word, combining EEG data to measure the accuracy of low-frequency speech envelope encoding. Reconstruction of EEG data revealed that dyslexic children showed significantly poorer synchronization accuracy for delta-band amplitude modulation than both age-matched and reading-level-matched controls (Power et al., 2016), again demonstrating impaired neural oscillation synchronization to delta-band temporal patterns in dyslexic children.

For dyslexic adults, Lehongre et al. (2013) examined neural oscillation characteristics in auditory cortex while participants watched a movie. Results showed no significant differences between dyslexic and control adults in delta-theta bands, but dyslexic adults lost gamma oscillation lateralization compared to typical adults. The researchers suggested that this abnormal neural oscillation interferes with phoneme acquisition and representation (Lehongre et al., 2013). Van Hirtum et al. (2019) used non-speech auditory stimuli to examine neural oscillation synchronization in dyslexic adults by measuring auditory steady-state responses (ASSR) to amplitude-modulated stimuli at different envelope rise times in theta (4 Hz), alpha (10 Hz), beta (20 Hz), and low-frequency gamma (40 Hz) bands. Results showed that dyslexic adults had lower signal-to-noise ratios (SNR) and weaker neural oscillation synchronization than typical adults in alpha, beta, and low-frequency gamma bands, with this effect occurring only at shorter rise times in alpha and beta bands. This abnormal neural synchronization to speech signals does not stem from language-level processing deficits but from sensory deficits in perceiving temporal cues embedded in speech (van Hirtum et al., 2019). These non-speech neural findings, together with behavioral results, support the view that dyslexic temporal processing deficits represent a broad cognitive dysfunction occurring at basic sensory levels that transcends stimulus features and task demands (Zhang et al., 2018). These neural studies demonstrate that temporal sampling deficits and inefficient phase-locking at one or multiple frequencies can explain cross-linguistic abnormal phonological development in dyslexia (Casini et al., 2018), and also reflect developmental characteristics of auditory temporal processing, with dyslexic children showing abnormal neural synchronization primarily in low-frequency temporal modulation (e.g., delta band; Power et al., 2013, 2016), whereas dyslexic adults show abnormalities primarily in high-frequency temporal modulation (e.g., gamma band; Lehongre et al., 2013; van Hirtum et al., 2019). Goswami (2011) proposed the Temporal Sampling Framework (TSF) model, integrating dyslexic difficulties in perceiving amplitude envelope rise time with impaired temporal sampling of input information by low-frequency (delta and theta band) neural oscillatory mechanisms to account for abnormal temporal coding and sensory deficits in speech perception. According to TSF, dyslexics are likely to show phonological deficits because basic auditory processing is abnormal from birth; infant deficits in processing low-frequency temporal modulation weaken prosodic sensitivity and impair speech development (Goswami, 2011). Therefore, abnormal responses to low-frequency temporal modulation are more likely to appear in early developmental stages (Cutini et al., 2016). Gamma-band amplitude modulation (Goswami & Leong, 2013) and duration (Rufener et al., 2019) correspond to phoneme representation and processing, and phoneme awareness is a consequence of learning to read (Ziegler & Goswami, 2005). Consequently, abnormal gamma oscillatory activity emerges during schooling when grapheme-phoneme learning is integrated into neural representations of speech (Cutini et al., 2016). These neural oscillation synchronization studies also suggest that dyslexic auditory temporal processing deficits may exist across broader temporal domains, with developmental patterns hinting that the temporal windows of deficit may narrow with age—questions that warrant further investigation.

4 Summary and Outlook

In summary, auditory temporal processing deficits represent a general sensory deficit originating at basic sensory levels that transcends language and age, and may constitute the core deficit underlying phonological impairments in developmental dyslexia. However, current research on auditory temporal processing deficits in dyslexia leaves many questions insufficiently addressed, requiring deeper investigation in the following areas. (1) **The temporal windows of dyslexic auditory temporal processing deficits and their developmental characteristics.** Since different temporal windows (40–4000 ms) correspond to different linguistic units (e.g., syllables, words, prosodic phrases), and cross-linguistic phonological awareness development progresses from larger-grain units (e.g., stressed syllables) to smaller-grain units (e.g., phonemes) (Goswami, 2018), we speculate that dyslexic auditory temporal processing deficits may exist only in temporal windows corresponding to linguistic components, and that these windows may narrow with age. Future cross-sectional and longitudinal studies should examine this issue. (2) **Whether auditory temporal processing deficits are a primary deficit in dyslexia or secondary to attention and working memory deficits.** Previous research indicates that dyslexics also exhibit attention and working memory deficits, yet tasks such as TOJ used in prior studies have not controlled for these factors. Future studies should include control conditions to determine whether auditory temporal processing deficits are primary. (3) **The neural time course of auditory temporal processing in dyslexia.** N1, P2, CNV (contingent negative variation), and

LPCt (late positive component of timing) correspond to selective attention, cognitive resource allocation, temporal encoding, and temporal discrimination in temporal processing, respectively. However, current neural research has only confirmed dyslexic auditory temporal processing deficits through MMN, without identifying at which processing stage these deficits occur. Future research using high-temporal-resolution ERP technology should explore this question to enhance understanding of the neural mechanisms underlying dyslexic auditory temporal processing deficits.

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Note: Figure translations are in progress. See original paper for figures.