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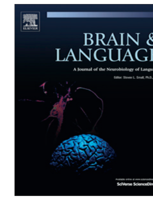

Atypical neural synchronization to speech envelope modulations in dyslexia

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ABSTRACT

A fundamental deficit in the synchronization of neural oscillations to temporal information in speech could underlie phonological processing problems in dyslexia. In this study, the hypothesis of a neural synchronization impairment is investigated more specifically as a function of different neural oscillatory bands and temporal information rates in speech. Auditory steady-state responses to 4, 10, 20 and 40 Hz modulations were recorded in normal reading and dyslexic adolescents to measure neural synchronization of theta, alpha, beta and low-gamma oscillations to syllabic and phonemic rate information. In comparison to normal readers, dyslexic readers showed reduced non-synchronized theta activity, reduced synchronized alpha activity and enhanced synchronized beta activity. Positive correlations between alpha synchronization and phonological skills were found in normal readers, but were absent in dyslexic readers. In contrast, dyslexic readers exhibited positive correlations between beta synchronization and phonological skills. Together, these results suggest that auditory neural synchronization of alpha and beta oscillations is atypical in dyslexia, indicating deviant neural processing of both syllabic and phonemic rate information. Impaired synchronization of alpha oscillations in particular demonstrated to be the most prominent neural anomaly possibly hampering speech and phonological processing in dyslexic readers.

1. Introduction

Developmental dyslexia refers to a hereditary neurological disorder characterized by severe and persistent difficulties in reading and spelling despite normal intelligence, education and intense remedial effort. Depending on the used criteria, dyslexia is thought to affect between 5 and 10% of the population (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Although it is widely agreed that the majority of dyslexic individuals show difficulties in one or several aspects of phonological processing, the underlying cause of these phonological problems remains debated. Recent evidence suggests that a fundamental deficit in synchronization of neural oscillations to temporal information in speech could underlie the phonological processing problems found in dyslexia (Goswami, 2011).

Temporal information in speech, most prominently represented as amplitude modulations in the speech envelope between 2 and 50 Hz (Rosen, 1992), is crucial for accurate speech perception (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The lower end of the speech envelope modulation range (between 2 and 12 Hz) hereby provides information on syllabic patterns (Edwards & Chang, 2013; Greenberg, Carvey, Hitchcock, & Chang, 2003), whereas the higher end of this range (between 12 and 50 Hz) provides information on phonemic patterns (Chait, Greenberg, Arai, Simon, & Poeppel, 2015; Leong & Goswami, 2014). Given the importance of temporal information for speech perception, it is of particular interest to understand how these syllabic and phonemic modulation rates are processed in the human auditory cortex. In this context, recent studies have assigned a fundamental role to neural oscillations by means of neural synchronization (Giraud & Poeppel, 2012; Peelle & Davis, 2012). It has been shown that neural populations in the auditory cortex synchronize their oscillatory activity in a rate-dependent manner to incoming temporal information. More specifically, the neural theta band (4–8 Hz) has been associated with sampling of events of

Abbreviations: ASSR(s), auditory steady-state response(s); SNR, signal-to-noise ratio.

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lower temporal precision, coinciding with the typical rates of syllabic patterns (Doelling, Arnal, Ghitza, & Poeppel, 2014; Ghitza, 2013; Ghitza, Giraud, & Poeppel, 2012; Luo & Poeppel, 2007), whereas the neural beta (13–30 Hz) and gamma (> 30 Hz) band sample events that require higher temporal precision, such as phonemic rate patterns (Bidelman, 2015; Han, Mody, & Ahlfors, 2012).

To examine whether an impairment in synchronization of neural oscillations to phonologically relevant patterns in speech could be related to the phonological processing problems in dyslexia, previous studies have focused on different oscillatory ranges. As a measure for syllable rate processing, modulations around 4 Hz are typically used. In general, results from these studies indicate no deviances in neural synchronization of theta oscillations in adults with dyslexia (Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012; Poelmans, Luts, Vandermosten, Boets, et al., 2012) nor in pre-reading children with a hereditary risk for dyslexia (Vanvooren, Poelmans, Hofmann, Ghesquière, & Wouters, 2014). On the other hand, modulations of 20 Hz and higher have been used as a measure for phoneme rate processing. Regarding these beta and low-gamma ranges, inconsistent results have been found, with dyslexic readers showing reduced synchronization in the left hemisphere (Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011; Poelmans, Luts, Vandermosten, Boets, et al., 2012), increased synchronization in the right hemisphere (Lizarazu et al., 2015) or no synchronization deficit (Hämäläinen et al., 2012). Based on these findings, the dyslexic brain seems to be characterized by atypical synchronizing behavior of beta or low-gamma neural oscillations, while no clear impairments are found regarding theta synchronization.

Strikingly, research in dyslexia is characterized by a lack of interest in auditory neural synchronization of alpha rates (8–13 Hz). The lower end of the speech envelope modulation range, representing syllable rate information, however includes modulations up to 12 Hz. Next to theta oscillations, an additional role for encoding of syllable rate information therefore seems to be attributable to auditory alpha range oscillatory activity. Initial evidence for this hypothesis is provided by Shahin and Pitt (2012), who found that alpha, not theta, oscillations supported neurophysiological mechanisms of speech segmentation. Additionally, a growing number of studies suggests that alpha oscillations are not only implicated in speech perception by means of bottom-up neural encoding, but also by exerting excitatory and inhibitory influences controlled by top-down processes (Kayser, Ince, Gross, & Kayser, 2015; Obleser & Weisz, 2012; Weisz, Hartmann, Müller, Lorenz, & Obleser, 2011; Weisz, Müller, Jatzev, & Bertrand, 2014; Weisz & Obleser, 2014; for a more general review, see Klimesch, Sauseng, & Hanslmayr, 2007). More specifically, alpha oscillations are thought to regulate auditory selective attention, a top-down process facilitating neural tracking of speech by selectively attending to relevant information and ignoring irrelevant information. Auditory selective attention has been related to speech-in-noise perception (Strauß, Wöstmann, & Obleser, 2014) as well as phonological skills (Yoncheva, Maurer, Zevin, & McCandliss, 2014). Given that dyslexic readers exhibit both speech and phonological processing problems, these novel insights urge for an investigation of auditory alpha oscillations in dyslexia.

In the present study, auditory neural synchronization is evaluated in a group of normal reading and dyslexic adolescents in four oscillatory bands (theta, alpha, beta and low-gamma), corresponding to two speech envelope frequency ranges (syllabic and phonemic). Besides neural synchronization to specific modulation frequencies, we also investigate the behavior of surrounding neural band activity during auditory processing. Despite recent findings assigning a unique role to alpha oscillations for speech perception in normal readers, alpha rate synchronization has not yet been extensively examined in dyslexia. Our study is the first to address four different oscillatory bands, including alpha, to examine whether a fundamental deficit in the functional role of neural oscillations is related to the phonological processing problems found in dyslexia.

2. Materials and methods

2.1. Participants

Fifty-three adolescents participated in this study, 21 normal reading adolescents (10 male, 11 female) and 32 dyslexic adolescents (15 male, 17 female; Table 1). All participants had bilateral normal hearing (pure tone average at 500, 1000 and 2000 Hz < 25 dB HL), normal nonverbal intelligence (IQ score $\geqslant$ 80; Kort et al., 2005; Wechsler, 1991) and no history of brain injury or neurological disorders. Participants were classified as normal or dyslexic readers based on their history of reading problems and their current reading performance. Dyslexic readers were required to (1) dispose of a formal clinical dyslexia diagnosis or report a life-long history of reading problems, and (2) score below percentile 10 on both a standardized word reading (Brus & Voeten, 1973) and pseudoword reading test (van den Bos, Spelberg, Scheepstra, & De Vries, 1994). Normal readers were required to (1) report no history of reading problems, and (2) score above percentile 10 on both reading tests. In addition to word and pseudoword reading, phonological awareness was also assessed by means of a spoonerisms test (Poelmans et al., 2011).

This study was approved by the Medical Ethical Committee of the University Hospitals of Leuven. All participants and their parents gave written informed consent.

2.2. Auditory steady-state responses

Auditory-steady-state responses (ASSRs) provide an interesting neurophysiological paradigm to measure synchronization of neural oscillations in the auditory cortex. ASSRs are defined as frequency and phase locked (i.e. synchronized) responses, which appear in the EEG when a stimulus with a periodic character is presented to the auditory system (Picton, John, Dimitrijevic, & Purcell, 2003). Because the periodic parameters of ASSR stimuli can be controllably adjusted to match the temporal rates at which meaningful phonological components occur in speech, ASSRs have been suggested to offer an objective measure for the ability of the auditory system to encode the different time scales represented in the speech envelope (e.g. Miyazaki, Thompson, Fujioka, & Ross, 2013; Tang, Brock, & Johnson, 2016; Tang, Crain, & Johnson, 2016). A number of studies have indeed demonstrated significant correlations between ASSRs and speech perception (Alaerts, Luts, Hofmann, & Wouters, 2009; Dimitrijevic, John, & Picton, 2004; Manju, Gopika, & Arivudai Nambi, 2014; Poelmans, Luts, Vandermosten, Boets, et al., 2012), thereby consolidating the link between low-level auditory temporal processing and speech perception.

2.2.1. Stimulus parameters

The stimuli used in the present study consisted of amplitude modulated speech-weighted noise. The carrier noise was adopted from the "Leuven Intelligibility Sentence Test" (van Wieringen & Wouters, 2008) and represents the long-term average speech spectrum of 730 sentences of a female speaker. The speech-weighted carrier noise was 100% amplitude modulated at approximately 4, 10, 20 and 40 Hz to measure neural synchronization of theta, alpha, beta and gamma oscillations respectively. The spectrum (dB/Hz) of the carrier wave, as well as the time signals of the