Deviant neural processing of phonotactic probabilities in adults with dyslexia
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During language acquisition in the first year of life, children become sensitive to phonotactic probabilities such as the likelihood of speech sound occurrences in the ambient language. Because this sensitivity is acquired at an early age, the extent to which the neural system that underlies speech processing in adults is tuned to these phonological regularities can reflect difficulties in processing language-specific phonological regularities that can persist into adulthood. Here, we examined the neural processing of phonotactic probabilities in 18 adults with dyslexia and 18 non-dyslexic controls using mismatch negativity, a pre-attentive neurophysiological response. Stimuli that differed in phonotactic probability elicited similar mismatch negativity responses among the adults with dyslexia, whereas the controls responded more strongly to stimuli with a high phonotactic probability than to stimuli with a low phonotactic probability, suggesting that controls – but not adults with dyslexia – are sensitive to the phonological regularities of the ambient language. These findings suggest that the underlying neural system in adults with dyslexia is not properly tuned to language-specific phonological regularities, which may partially account for the phonological deficits that are often reported in dyslexic individuals. NeuroReport 24:746–750 © 2013 Wolters Kluwer Health | Lippincott Williams & Wilkins

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Introduction

Accurate phonological representations are required for the proper development of efficient reading and writing skills. Difficulty mapping letters to sounds can be associated with language disorders such as developmental dyslexia [1]. Developmental dyslexia is defined as a specific reading disorder characterised by severe and persistent impaired reading and spelling and is not explained by either sensory or cognitive deficits or by a lack of effective instruction [2]. It is widely accepted that the most commonly occurring cognitive deficit in dyslexia is difficulty representing and processing speech [3]. Furthermore, several neuroimaging studies in dyslexia have provided evidence for functional anomalies in brain areas not only associated with phonological processing but also with orthographic processing [4–7]. Although such additional orthographic deficits may contribute to poor reading skills in dyslexia, longitudinal studies show that phonological processing in young children predicts later reading success [1,3]. However, to date, neural studies that investigate impaired processing of relatively higher level phonological information in dyslexia such as phonotactic probabilities – that is the likelihood of speech sound occurrences in a language – have been carried out only in children [8]. Thus, difficulties in the neural processing of phonotactic probabilities might also be an underlying factor in adults with dyslexia; however, the question of whether such difficulties can persist into adulthood has remained unanswered. Therefore, we focused on the neural processing of phonotactic probabilities both in adults with dyslexia and in typically reading controls.

During language acquisition, infants become sensitive to the phonological regularities of the ambient language in the first year of life, and this sensitivity then facilitates the acquisition, recognition and representation of spoken language later in life [9]. Because every language contains specific phonological regularities, learning these statistical regularities requires exposure to the language. Because of this requirement, studying the extent to which the neural system that underlies speech processing is tuned to these statistical language regularities can provide a useful method to investigate the specification of phonological representations. In individuals with dyslexia, such representations may not be properly tuned to the ambient language, and this lack of tuning can affect the processing of phonological regularities.

Phonological processing in dyslexic individuals is usually measured using behavioural tasks that require overt responses. However, a limitation of this approach is that these tasks will inherently reflect attentional, motivational and task-related artefacts and therefore may not...
reliably capture subtle underlying deficits in speech processing. Unlike behavioural measures, measuring event-related potentials (ERP) is a more appropriate method for investigating online phonological processing difficulties. Therefore, we used mismatch negativity (MMN) to measure the neural processing of phonological regularities in normal-reading adults and dyslexic adults. The MMN reflects an automatic change detection response and is typically recorded using an oddball paradigm in which the MMN is elicited by any noticeable change in the preceding auditory stimulus sequence, irrespective of attention or the behavioural task (for a review, see Näätänen et al. [10]). Furthermore, the MMN can provide an index of experience-dependent memory traces and is sensitive to language-specific phoneme representations [10,11].

In the present study, an oddball paradigm was used in which syllables that differed in phonotactic probability were used once as a standard and once as a deviant to minimise the contribution of acoustic processes [8,12]. Based on a previous study of children with dyslexia and control children [8], we hypothesised that typically reading controls would exhibit an asymmetric MMN response pattern with larger amplitudes for a high phonotactic probability syllable, thus indicating sensitivity to phonotactic probabilities. On the other hand, if insensitivity to phonotactic probabilities persists into adulthood, adults with dyslexia should exhibit deviant neural processing in response to syllables with high versus low phonotactic probabilities.

Methods

Participants

Eighteen dyslexic adults (15 women and three men), mean age 20.95 years (SD = 2.61), participated in this study. A second group of 18 adults (12 women and six men), mean age of 21.28 years (SD = 2.56), served as a control group. Each adult with dyslexia was diagnosed by a qualified psychologist using an extensive standardised cognitive behavioural procedure. At the time of testing, the individual participant was seated comfortably in a semi-soundproof room. Each participant watched a self-selected silent movie and was instructed to ignore the auditory stimuli. The stimuli were presented using an oddball paradigm in which a sequence of identical stimuli (i.e. standards) was interrupted by a rare stimulus (i.e. deviant) with a probability of 0.12. The experiment was divided into four blocks of 400 stimuli each (48 deviants and 352 standards), in which the stimuli were presented with a stimulus-onset asynchrony of 600 ms.

Stimuli

The standard and deviant stimuli were sine-wave analogues of the speech sounds /b/ and /d/ (consonants /b/ and /d/ followed by the neutral vowel /a/; schwa) and were generated using parallel formant synthesis (for further details, see Noordenbos et al. [15]). The phonotactic probability of the stimuli was determined by computing the type and token frequency using CELEX [16], a corpus based on 42 million Dutch words. The log frequencies of the sequence /da/ were higher with respect to both type (4.85) and token (6.69) than the respective log frequencies of the sequence /ba/ (type: 4.22, token: 5.91). Note that the 0.78 difference in token log frequency reflects the six-fold difference in the number of Dutch words containing the sequence /da/ compared to the number of Dutch words that contain the sequence /ba/. The syllable /ba/ – which had a low phonotactic probability (LPP) – had rising F2 and F3 transitions (rising F2: from 1094 to 1500 Hz; rising F3: from 2024 to 2500 Hz), whereas the syllable /da/ – which had a high phonotactic probability (HPP) – had falling F2 and F3 transitions (falling F2: from 1853 to 1500 Hz; falling F3: from 3429 to 2500 Hz). The end frequencies of the F2 and F3 transitions were fixed at 1500 and 2500 Hz, respectively. The initial and end frequencies of the first formant (F1) were 300 and 500 Hz, respectively. The voice onset time was 80 ms, the duration of each frequency transition was 40 ms and the duration of the stable vocalic segment was 80 ms; thus, the total duration of each stimulus was 200 ms.

Electroencephalogram recording and procedure

The electroencephalogram (EEG) was amplified using a BrainAmp DC amplifier (Brain Products GmbH, Gilching, Germany), band-pass filtered at 0.1–200 Hz and sampled at a rate of 500 Hz. The EEG was recorded using Ag/AgCl electrodes that were placed at 26 scalp sites in accordance with the International 10–20 system (ActiCap system; Brain Products GmbH). Each electrode was referenced online to the tip of the nose. Additional electrodes were placed on the left and right mastoids. The horizontal and vertical electro-oculograms (EOG) were monitored using electrodes placed at the left and right external canthi of the eyes (for the horizontal EOG) and above and below the left eye (for the vertical EOG). The impedance of each electrode was less than 10 kΩ. The EEG was recorded while the individual participant was seated comfortably in a semi-soundproof room. Each participant watched a self-selected silent movie and was instructed to ignore the auditory stimuli. The stimuli were presented using an oddball paradigm in which a sequence of identical stimuli (i.e. standards) was interrupted by a rare stimulus (i.e. deviant) with a probability of 0.12. The experiment was conducted in accordance with the ethical guidelines of the Behavioural Science Institute at Radboud University Nijmegen.
stimuli were presented between two successive deviant stimuli. For each participant, a unique stimulus presentation list was created. The stimuli were binaurally delivered using Sennheiser model HD 555 headphones (Sennheiser, Wedemark, Germany) set at a comfortable hearing level of ~65 dB. The presentation of the stimuli was controlled by Presentation software (Neurobehavioral Systems Inc., Albany, California, USA).

Data analysis

The continuous EEG data were pre-processed and analysed using the open source Fieldtrip toolbox [17]. Ocular artefacts in the EEG data were removed using independent component analysis (see Jung et al. [18]). Any residual artefacts in the EEG data that exceeded a voltage change of ±75 μV at any electrode were excluded from further analysis (3% of the trials met this criterion). The EEG data were re-referenced to the mean of the two mastoid electrodes, and ERPs were calculated by averaging the data from -100 through +600 ms relative to the stimulus onset for the standards and deviants. The epochs were digitally filtered using a 1–30 Hz band-pass filter and baseline-corrected with respect to the 100 ms pre-stimulus interval. Only the standard immediately preceding the deviant was included in the analysis, thereby yielding a signal-to-noise ratio that was similar between the standard and the deviant.

The MMN was obtained by subtracting the ERPs that were elicited by the standard from the ERPs that were elicited by the deviant for physically identical stimuli. The grand-mean MMN peak was identified from the difference waveform at electrode Fz [10,19] as the most negative peak occurring between 150 and 400 ms after the stimulus onset. At Fz the MMN response was visibly detectable in both groups, as was an inverted polarity below the Sylvian fissure (at the mastoid electrodes). The individual mean MMN amplitudes were averaged across a 50 ms time window surrounding the grand-mean MMN peak latency at Fz. To test whether the MMN mean amplitudes differed significantly from baseline (measured from -100 to 0 ms), a cluster-based random permutation procedure that included all EEG channels was applied to minimise the likelihood of a Type I error in the case of multiple comparisons. In particular, the data were randomised between conditions for several iterations (in this study, 1000 times). For each of these randomisations, cluster-level statistics were computed based on t-scores, and the largest cluster-level statistic was entered into the null distribution. The P-value was estimated as the proportion of randomisations with a more extreme test statistic than the observed test statistic (for more details, see Maris and Oostenveld [20]).

Results

As shown in Fig. 1a, the HPP syllable elicited a large MMN response in both the adults with dyslexia (−1.6 ± 1.6 μV, mean ± SD) and the controls (−1.4 ± 2.2 μV); in contrast, the LPP syllable elicited an MMN response in the adults with dyslexia (−1.0 ± 1.6 μV) but not in the controls (0.3 ± 1.5 μV). The cluster-based random permutation analysis revealed that the MMNs for the HPP syllable in both the adults with dyslexia and the controls differed significantly [t(17) = 80.84, P < 0.001 and t(17) = 42.02, P = 0.005, respectively] from baseline at several fronto-central electrodes (these electrodes are shown as white stars in the topographies in Fig. 1). With respect to the LPP syllable, cluster-based statistics revealed a significant MMN in the adults with dyslexia [t(17) = 37.69, P = 0.02] but not in the controls; in the control group, no clusters for the LPP syllable differed significantly from baseline.

Next, for both the HPP and the LPP syllables, the ERP responses of the adults with dyslexia were compared with the control responses (Fig. 1b). With respect to the HPP syllable, cluster-based statistics did not reveal any significant clusters. In contrast, with respect to the LPP syllable, cluster-based statistics revealed a frontally distributed cluster that was significant [t(34) = 15.81, P = 0.02]; specifically, the adults with dyslexia exhibited larger fronto-central negativity for the LPP syllable.

No significant correlation was observed between the MMN amplitude and reading skill.

Discussion

The findings of the present study revealed that high-functioning adults with dyslexia have deviant pre-attentive brain responses to language-specific phonological regularities compared to typically reading adult controls. The typically reading adults had higher MMN responses to the sequence with HPP relative to the sequence with LPP, and this finding is consistent with previous studies of typically reading adults and children [8,21]. More importantly, the MMN responses of the adults with dyslexia did not reflect any sensitivity to these language-specific phonological regularities. The adults with dyslexia had comparable MMN responses to speech sound sequences with both high and low phonotactic probabilities. These results support the hypothesis that the processing of language-specific phonological information is impaired in dyslexic individuals.

However, other factors may account for the present findings and should be considered. Because the MMN responses that are elicited by speech stimuli can reflect both acoustic-specific and phoneme-specific processes [11], it may be argued that our results could have been influenced by low-level acoustic-related stimuli effects. However, we used an oddball paradigm in which each stimulus was used once as a standard and once as a deviant to minimise the contribution of acoustic processes. Furthermore, because only the standard that immediately preceded the deviant was included in the analysis, the signal-to-noise ratio was similar for the standard and
deviant stimuli. It is therefore unlikely that the differences in the ERP responses between the standard and the deviant stimuli are a result of differences in the physical stimuli.

Alternatively, our results may reflect the sparse phonological representations of coronals (e.g., /d/) that have been found for typically reading individuals. According to this model of underspecification, only contrastive or otherwise non-predictable information of speech sounds is stored in the mental lexicon [22]. Thus, depending on the features extracted from the speech signal and depending on the presence or absence of these features in the mental lexicon, this model predicts asymmetric activation patterns [22]. The present results of the control group are consistent with these expectations in that the coronal deviant /d/ elicited a larger MMN response than the noncoronal deviant /b/. However, such an explanation was proposed previously in a study of phonotactic probability and the MMN [21], which found a larger MMN for the coronal [s] than for the labial [f] in typically reading adults when these sounds were embedded in their respective sequences with high or low phonotactic probabilities. To disentangle phonotactic probability and coronality, the authors tested whether this asymmetry persisted when [s] and [f] occurred in sequences with similar phonotactic probability. The asymmetry did not persist, thereby contradicting the predictions of phonological underspecification. In addition, several eye-tracking [23] and behavioural [24,25] experiments contradict the predictions made by models of phonological underspecification, thus making it difficult to consider coronal underspecification as a viable theory.

**Conclusion**

Our finding of comparable MMN responses to phoneme sequences with high and low phonotactic probability in adults with dyslexia provides evidence of a deficit in the early neural processing of language-specific phonological information. Difficulties in the neural reception and encoding of speech stimuli can negatively impact the implicit learning of phonological regularities within the
language, particularly in the first year of life, during which children become sensitive to the statistical regularities present in the ambient language. Although it is well-established that phonological deficits play a prominent role in difficulties with the mapping of letters to sounds, recent neuroimaging results indicate that additional processing deficits might also play a role in reading difficulties [4]. Based on the present findings, it is important to note that the cognitive difficulties underlying the processing of language-specific phonological regularities can persist into adulthood, even in high-functioning adults with dyslexia. Moreover, because phonological skills are usually assessed using behavioral measures, these subtle phonological difficulties can remain unnoticed in adults with dyslexia who have years of reading experience.

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**References**