Speaking of reading: The role of basic auditory and speech processing in the manifestation of dyslexia in children at familial risk
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Chapter 3

Neural processing of natural speech phonemes and words is related to reading problems and not to familial risk at the end of primary school: an ERP study

This study investigated speech processing and its lateralization in children with a familial risk (FR) of dyslexia who have become good (FRND) and poor readers (FRD) and controls at the end of primary school. By comparing these three groups, factors that relate to FR and factors that relate to reading can be discerned. Processing of phonemes and words was investigated using event-related potentials (ERP). ERP components of interest are components reflective of auditory change detection; the mismatch negativity (MMN) and late discriminative negativity (LDN). Attenuated LDNs to phonemes and words were observed in FRD children, compared to controls and FRND children. Reading status was predictive of LDN amplitude, not FR status. There were no differences in hemispheric lateralization between groups; the left hemisphere was dominant in processing speech. Overall, attenuations in speech processing are associated with poor reading.

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Introduction

To be able to become a fluent reader, a child needs apt reading related skills such as rapid automatized naming and phonological processing (Pennington & Lefly, 2001; De Jong & Van der Leij, 2003) in order to be able to swiftly and accurately connect speech sounds (phonemes) to their written counterparts, graphemes (letters). Low awareness of the phonological structure of language can ultimately lead to persisting reading difficulties. If poor reading skills are not attributable to a low intelligence, sensory deficits or environmental factors such as poor educational opportunities, we speak of dyslexia (e.g. Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Research has shown that children whose parents have dyslexia have an increased risk of developing dyslexia, suggesting a genetic influence on the development of reading skill (for a review, see Carrion-Castillo, Franke & Fisher, 2013).

The idea that a deficit in phonological awareness is instrumental in the manifestation of dyslexia is widely accepted (Vellutino et al., 2004). It has been suggested that a decreased ability to process speech may be at the core of phonological problems; since a deficit therein would impede the formation of accurate representations of phonemes. This may in turn result in problems with phonological awareness and ultimately with reading (Tallal, 1980; Tallal, Miller and Fitch, 1993; Boets, Wouters, van Wieringen, de Smedt, and Ghesquière, 2008; MacAnally & Stein, 1996; Hämäläinen, Salminen, and Leppänen, 2013; Farmer & Klein, 1995).

Though previous research has brought forward the important role of genetics in reading problems (e.g. Carrion-Castillo et al., 2013), not all studies investigating speech processing and dyslexia distinguished participants with a familial risk background from participants without a familial risk. Taking this approach would be beneficial, especially after familial risk children have learned to read, as from that moment familial risk children with and without reading problems can be identified. This may provide the field with the opportunity to tease apart factors that are correlates of being at familial risk for dyslexia versus factors that directly influence reading fluency. In the first case, familial risk children with and without dyslexia will be affected, whereas in the latter case, only poor readers are affected. Therefore, the aim of the current study is to provide insight into the role of speech processing in familial risk children who became fluent readers, versus those who did not.
Speech processing in dyslexia

Several studies have looked into the relations between speech processing and reading on a behavioral level. Poor readers are often found to be impaired in detecting speech rhythm which is important for the segmentation of speech into words and syllables (Goswami et al., 2002), speech in noise perception (Boets et al., 2011), and categorical speech perception indicating poorer neural representations of phonemes (Boets et al., 2011; Manis et al., 1997). Their performance on these tasks is significantly weaker than that of fluent readers.

Multiple aspects of speech processing in dyslexia have also been investigated using event-related potentials (ERPs) (e.g. Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998; Hämäläinen, Leppänen, Gutorm, & Lyytinen, 2008; Noordenbos, Segers, Serniclaes, & Verhoeven, 2013), such as the Mismatch Negativity (MMN; Näätänen, 1995; Näätänen et al., 2012), and late discriminative negativity (LDN; e.g. Cheour, Korpilahti, Martynova, & Lang, 2001). The MMN is used as an index of auditory (speech) discrimination. It is considered a pre-attentive measure because it can be recorded while participants perform an unrelated primary task or watch a video (e.g. Näätänen et al., 2012), hence attentional confounds are minimized. MMN is typically elicited after an occasional deviant stimulus is presented in a train of repeated standard stimuli. It is thought that the repetition of the standard stimulus leads to the buildup of an auditory memory trace of regular sound features contained in the standard, such as pitch or a phoneme. The auditory system compares incoming sounds to the memory trace of the standard, and when a change is detected an MMN is elicited (Näätänen, 1995). The MMN is characterized by a frontally negative deflection in the ERP waveform, around 200 ms after deviance onset in adults. The LDN is related to MMN elicitation and is thought to reflect automatic processing of change in auditory and linguistic stimuli (Cheour et al., 2001). LDN is also characterized by a frontally negative deflection, which typically occurs between 300-600 ms after stimulus onset (Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001). LDN is observed in adults and children, though its amplitude appears to decrease throughout development (Ceponiene, Lepistö, Soininen, Aronen, Alku, & Näätänen, 2004).

Previous studies that use ERPs to investigate pre-attentive speech processing in poor readers seem to consistently find differences between poor readers and controls. For example, Noordenbos et al. (2013) show, in a study investigating phonotactic probabilities (i.e. the likelihood that a certain speech sound occurs in a given context) in dyslexic adults, that adults with dyslexia possibly do not have a neural system that is specifically tuned for
their ambient language. Dyslexic adults respond similarly to deviant stimuli with a high phonotactic probability as compared to ones with a low phonotactic probability, whereas controls show a larger MMN only to the first category. Such a deficit in extracting information from spoken language may lead to improper detection of speech features, which may ultimately result in poor reading skill. Lachmann, Berti, Kujala, and Schröger (2005) found 9-year-old dyslexic participants to have no MMN to speech stimuli compared to controls. Meng et al. (2005) found that in Chinese 11-year old dyslexic children, syllable processing was impeded. Furthermore, Schulte-Körne et al. (1998) found that poor reading children at age 12 had an attenuated MMN to speech stimuli but not to tone stimuli, compared to fluent readers. To investigate whether this speech processing deficit persisted into adulthood, Schulte-Körne et al. (2001) assessed speech processing in adults with dyslexia and showed that poor readers had an attenuated LDN to speech processing. Results from these studies thus suggest an attenuated MMN or LDN amplitude to speech stimuli to be present in poor readers of various ages.

A small number of familial risk studies addressing pre-attentive speech processing is available, though unfortunately not all studies could distinguish good- and poor reading at risk children. For example, Lovio, Näätänen, and Kujala (2010) investigated speech sound encoding in children at risk for dyslexia using ERPs in first grade. They found that children at risk for dyslexia had an attenuated MMN for several aspects of speech processing, such as vowel processing, vowel duration and intensity changes. Maurer et al. (2009) found that familial risk children in kindergarten had a less left lateralized LDN to phoneme changes compared to typical readers. These neurophysiological results uniquely contributed to predicting reading ability in fifth grade. Within the Dutch Dyslexia Programme (DDP; Van der Leij et al., 2013), pre-attentive speech processing has been studied as well. Van Zuijen, Plakas, Maassen, Maurits, and Van der Leij (2013) assessed processing of /bAk/ and /dAk/ at 2 months. They were able to retrospectively distinguish between good and poor readers in the at risk group after their reading skill was assessed in Grade 2. It turned out that fluent readers at risk of dyslexia and controls outperformed poorly reading children at risk of dyslexia in processing of speech at young age. When teasing apart familial risk and reading fluency, it thus appears that proficient speech processing is a characteristic of fluent readers. Our study aims to test whether attenuated speech processing of DDP children at the age of 12 is still related to poor reading skill, and not a correlate of being at familial risk for dyslexia.
Lateralization of speech and language processing in dyslexia

Research has not only focused on the proficiency level of speech processing in dyslexia, but also on possible differences in the networks underlying speech processing between good and poor readers. Language is typically dominant in the left hemisphere (LH; Dehaene et al., 1997). Indeed, functional imaging studies investigating reading processes in typical readers consistently show the involvement of LH ventral- and dorsal networks in phonological decoding and visual word recognition (for a review, see Sandak, Mencl, Frost, and Pugh, 2004). However, in dyslexia, several studies have shown that both the dorsal and ventral systems in the LH are less activated during reading compared to typical readers (Richlan, Kronbichler, and Wimmer, 2009; Sandak et al., 2004; Simos et al., 2002). Moreover, dyslexic readers show a heightened activation in the right hemisphere instead of the left hemisphere during reading and reading related phonological tasks (Shaywitz et al., 2002; Simos et al., 2002; Dufor, Serniclaes, Sprenger-Charolles, & Démonet, 2007). It thus appears that in poor readers, linguistic functions are less lateralized, possibly explaining more effortful reading (Sandak et al., 2004). Based on these neuroimaging results, one may expect similar patterns in ERP studies, such as a less lateralized MMN in dyslexia (Sebastian & Yasin, 2008). However, results from ERP studies addressing lateralization diverge. Although several studies underline the neuroimaging results in that they have shown that poor readers of various ages employ different processing networks (Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; for a review, see Pugh et al., 2000), ERP results have shown both left-, right-, and bilateral hemispheric activation for tone- and speech processing in dyslexia and children at risk (Kujala, Belitz, Tervaniemi, & Näätänen, 2003; Lovio et al., 2010, Lyytinen et al., 2005, van Herten et al., 2008, van Zuijen et al., 2013; Sebastian & Yasin, 2008; Schulte-Körne et al., 1998; Hakvoort, van der Leij, Maurits, Maassen, & van Zuijen, 2015; Maurer, Bucher, Brem, & Brandeis, 2003, Maurer et al., 2009). It is possible that these mixed findings are a result of the types of paradigm and stimuli used (Sebastian & Yasin, 2008). Shtyrov, Pihko, and Pulvermüller (2005) also addressed lateralization of speech (not in a clinical population) using ERPs and found that there was a reliable left lateralization only when the speech was comprised of words, not pseudowords or speech-like spectral sounds. Verbs specifically yielded a strong left lateralization of the MMN (Shtyrov et al., 2005), possibly because of the use of inflectional affixes (Pulvermüller, Lutzenberger, & Birbaumer, 1995; Shtyrov & Pulvermüller, 2002). Therefore, the current study addresses possible differential lateralization of speech processing in dyslexia by including an inflected verb paradigm.
The current study

The aim of the current study is to discern the role of familial risk versus that of reading fluency in pre-attentive speech processing and lateralization of speech processing. We did this by analyzing the performance of children at risk for dyslexia versus controls, and of fluent readers (controls and fluently reading familial risk children) versus poor readers. We assessed whether pre-attentive speech processing is related to deficits in reading at the age of 12, by measuring the ERPs of control children and familial risk children with and without reading problems enrolled in the DDP. We addressed speech processing through MMN and LDN using an oddball paradigm (Näätänen, 1995). We investigated differential lateralization of speech processing by comparing processing of natural speech phonemes and processing of spoken inflected verbs by using a phoneme contrast (/a:/ vs. /o:/), and the verb zie (“see”) versus its inflected form ziet (“sees”). Including a verb in our word paradigm, following Shtyrov et al. (2005), may lead to a more distinctly lateralized MMN or LDN compared to the phoneme condition. By including this paradigm we expect possible differences between groups to become more pronounced.

Methods

Participants

Fifty-five children, who comprised a sub-sample of children who previously participated in the DDP participated in the current study based on the following inclusion criteria.

If one or both parents were dyslexic, children were assigned to the familial risk (FR) group. The DDP parents in this sample have an above average educational background; 51% have successfully completed higher vocational or university, compared to 34% in the general population in the Netherlands (Centraal Bureau voor de Statisiek, 2013). Parents were presented with Dutch norm-referenced tests for word- and pseudoword reading to assess their reading fluency (Brus & Voeten, 1973; Van den Bos, Lutje Spelberg, Scheepstra, & De Vries, 1994; see Materials). Children were assigned to the familial risk group if their parents scored below the 15th percentile on either test and not higher than the 50th on the other, or below the 20th percentile on both tests. If parents scored above the 50th percentile on both the word- and pseudoword reading tests, children were assigned to the control group.

The development of children’s reading skills was monitored and children were included in the familial risk group with dyslexia (FRD), if the FR children performed poorly on a word-
and pseudoword reading test the last time that these tasks were administered in Grade 5 or 6 and at least on one out of the two times these tasks were administered earlier: at the end of 2nd grade and in Grade 3. Scores below the 10th percentile on one test and below the 40th percentile on the other test, or below the 25th percentile on both tests, was defined as a poor performance. If FR children did not match these criteria, they were included in the familial risk group without dyslexia (FRND) (Hakvoort et al., 2015).

ERP data from one child had to be omitted due to technical problems while recording the EEG. Incomplete data from two children had to be omitted from the phoneme condition. In total, data from 52 children were included in the analysis of the phoneme condition, and of 54 children for the word condition (32 boys). Informed consent was obtained from the parents of the participants. Information on background variables can be found in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Background Characteristics</th>
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<tr>
<td></td>
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<tr>
<td>Controls</td>
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<td>(n = 15)</td>
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<tr>
<td>Variable</td>
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<tr>
<td>M(SD)</td>
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<tr>
<td>Age (years)</td>
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<td>11.9 (0.6)</td>
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<td>WRF grade 6</td>
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<td>76.33 (11.06)</td>
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<td>PWF grade 6</td>
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<td>63.87 (18.05)</td>
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<td>78.77 (14.23)</td>
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<td>Verbal IQ grade 3</td>
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<tr>
<td>33.60 (4.76)</td>
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<td>FRND</td>
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<td>(n = 24)</td>
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<tr>
<td>WRF grade 6</td>
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<td>69.42 (9.38)</td>
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<td>48.58 (14.49)</td>
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<td>33.46 (4.86)</td>
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<td>FRD</td>
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<td>(n = 15)</td>
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<td>WRF grade 6</td>
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<td>PA grade 3</td>
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<tr>
<td>56.35 (18.95)</td>
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<td>PA grade 6</td>
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<td>74.44 (20.77)</td>
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<tr>
<td>Nonverbal IQ grade 3</td>
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<td>43.06 (10.87)</td>
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<tr>
<td>Verbal IQ grade 3</td>
</tr>
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<td>30.20 (6.06)</td>
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</tbody>
</table>

Note. FRND: Familial risk no dyslexia, FRD: familial risk dyslexia, WRF: number of words read accurately within one minute, PWF: number of pseudowords read accurately within two minutes. PA: Phonological awareness, measured by a phoneme deletion task and displayed in proportion of items correct. Nonverbal IQ and Verbal IQ are displayed in total number of points (raw score). All values are given as Mean (standard deviation). Shared subscripts are indicative of no significant difference. Significant differences are all p < .05.
Materials

Word-reading fluency. The “Een-minuut-test” (one minute test; Brus & Voeten, 1973) was used in Grade 3 and in Grade 5/6, and the second list of the “Drie Minuten Toets” was used (three minutes test; Verhoeven, 1995) in Grade 2 to measure and assess word reading fluency (WRF). The one minute test consists of a list of 116 mono- and polysyllabic words (e.g. “weg” [road], “vluchten” [to flee]) increasing in difficulty. The administered list of the three minutes test consists of 150 monosyllabic words. The score was the number of words read correctly in one minute for both tests.

Pseudoword-reading fluency. The Dutch norm-referenced task De Klepel (Van den Bos et al., 1994) measured pseudoword-reading fluency (PWF). It consists of a list of 116 mono- and polysyllabic pseudowords, such as “taaf”. The score was the number of words read correctly within two minutes.

Phonological awareness. Phonological awareness was assessed using a phoneme deletion task (De Jong & Van der Leij, 2003). In Grade 3, the task was administered orally; stimuli were read by the experimenter. The test comprised three parts. The first and the second part consisted of 9 mono- and 9 bisyllabic pseudowords, respectively. Children were asked to delete one consonant phoneme. For example, the word “skoom” without /k/ would become “soom” and “memslos” without /l/ would become “memsos”. During the third part, children were presented with 9 bisyllabic pseudowords. The consonant they were asked to delete occurred twice; for example “gepgral” without /g/ would become “epral”. When six consecutive items were answered incorrectly in the first, or three in the second part, the test ended. The score on this task was the total number of items correct.

In Grade 6, the test was computerized and shortened; four trials were presented per part. Stimuli were similar to those in the Grade 3 test and presented through headphones. Two practice items preceded the first and third parts of the test. The score on this task was the total number of items correct.

Nonverbal IQ. To measure nonverbal IQ in grade 3, the Block Design subtest of the WISC III (Wechsler, 2005) was used. Children completed block designs with coloured blocks, using an example presented to them on a card. First, an experimenter demonstrated the task. Then the participant was asked to complete the design according to the card. Each trial had a time limit of 45 seconds. The number of blocks that had to be used per trial
increased. The maximum number of trials was 15. The task ended when the child failed or exceeded the time limit on two consecutive trials.

**Verbal IQ.** To measure productive vocabulary in grade 3, the Vocabulary subtest of the WISC III was used (Wechsler, 2005). The children were asked to give the meaning of words (e.g. What is a tree?). In total, there were 35 items. Each item was awarded with 0, 1, or 2 points depending on the description given. If four subsequent items rendered a score of 0, the task was aborted. The maximum score was 70.

**Stimuli**

Stimuli were all pronounced by a native speaker of Dutch and edited using Adobe Audition (Adobe Systems Inc., San Jose, USA). Stimuli were presented by using an oddball paradigm. In the phoneme condition, stimuli were natural speech phonemes /a:/ and /o:/, as previous work by Csépe (2003) has suggested that the rounding feature elicits the clearest mismatch response. The standard stimulus, /a:/, had a duration of 234 ms and the deviant stimulus, /o:/, a duration of 312 ms. The stimulus onset asynchrony (SOA) was 750 ms. In the word condition, the standard stimulus was the word “zie” (see) and the deviant stimulus the word “ziet” (sees). To keep the stimuli as constant as possible, the standard was created by using the deviant stimulus ziet and removing /t/ from the recording. The deviant /t/ was pronounced at 420 ms, resulting in deviant onset at 420 ms. The SOA was 950 ms. In both the phoneme and word condition, deviants were presented randomly and had a probability of 13%. Each participant was offered 3 blocks per condition. The beginning of each experimental block was marked by a sequence of 4 standard stimuli, after which standards and deviants were presented randomly with the constraint that no deviant occurred twice in a row. In total, the standard stimulus occurred 641 times per block. In total, 96 deviants were presented per block.

**Procedure**

**Data collection.** The EEG recording took approximately thirty minutes per condition and was part of a longer recording session of approximately 3 hours including preparation time, in which a total of four paradigms were offered in a fixed order. The paradigms described in this study were recorded second (words) and last (phonemes). Upon arrival, the children were familiarized with the procedure. During the EEG recording they were seated in a comfortable chair and watched a silent movie with subtitles, while being presented with the
stimuli through headphones. The child was monitored by the experimenter in an adjacent room. The experimenter attended to the child between blocks. Breaks were taken when necessary. Behavioral tasks were administered in a separate session on a separate day in a quiet room. This session took approximately two hours. Our research procedures were approved by the Ethics Committee of the Faculty of Social and Behavioural Sciences, Child Development and Education Department of the University of Amsterdam.

**EEG recording & analysis.** The EEG was recorded using ActiView (BioSemi, Amsterdam, The Netherlands), at a sampling rate of 1024Hz/channel with an online band pass filter of 0.01-100 Hz. Children wore a 64-electrode EEG cap (BioSemi, Amsterdam, The Netherlands). The electrodes were positioned according to the international 10-20 system (Jasper, 1958). A total of four electro-oculogram (EOG) electrodes registered eye blinks and eye-movements. Additionally, electrodes were attached to the mastoids and nose. The latter was used as a reference.

Brain Vision Analyzer (Brain Vision Analyzer software, Brain Products GmbH, Munich) was used to analyze the data. Data were first downsampled to 512 Hz. The EEG was bandpass filtered offline between 1 Hz (12dB/oct) and 30 Hz (12 dB/oct). Independent Component Analysis (ICA) on all channels (64 and reference) was used to identify eye-blink artifacts. Presence of eyeblinks was verified by checking the frontal scalp distributions, which had to have a positive polarity, and by making ICA Backtransforms. Only components that contained blinks were removed. The signal in the phoneme condition was segmented between –150 and 750 ms relative to stimulus onset and baseline corrected (–150 – 0 ms relative to stimulus onset). For the word condition, the signal was segmented between -150 to 950 ms relative to stimulus onset and baseline corrected until deviance (/t/) onset (-150-400 ms).

Any trial with amplitudes exceeding +/- 150 µV was seen as containing artefacts and not included for further analysis. Next, averages were calculated for the standard and deviant stimulus. The minimum number of deviants included per participant in the phoneme condition was 93 ($M = 191$) and 106 ($M = 193$) in the word condition. Additionally, difference waves (deviant minus standard) were calculated for each condition and grand average difference waves of the control group were examined to determine peak latencies of MMN and LDN, i.e. the moment in time at which the average difference in amplitude between standard and deviant stimuli was largest. To assess the role of familial risk versus reading fluency in speech processing, we addressed potential differences between familial
risk children (FRND and FRD children) and controls, and consequently addressed potential differences between fluent readers (controls and FRND children) and poor readers (FRD children) using planned contrasts.

Results

LDN

ERPs in the phoneme condition (Figure 1) show a positive deflection around 100 ms for the standard stimulus /a:/, followed by a negative deflection starting around 200 ms. A positive deflection can be seen around 150 ms for the deviant stimulus /o:/, followed by a negative deflection starting around 300 ms. In the phoneme condition, no clear MMN could be identified. However, visual inspection of the ERP waveforms suggests an LDN to be present and to stretch from 510 to approximately 590 ms, peaking around 550 ms at electrode F4. A window of 80 ms around the peak (510-590 ms) was chosen for analysis.

ERPs in the word condition (Figure 2) show a positive deflection starting around 150 ms, followed by a negative peak starting around 450 ms. In the word condition, visual inspection of the ERP waveforms again does not point toward a clear MMN, but suggests an LDN to be present and to start around 300 ms after deviance onset advancing all the way to approximately 500 ms after deviance onset (from 700-900 ms, peaking around 800 ms at electrode F4). Therefore, a window of 200 ms around the peak was chosen to address LDN presence (700-900 ms).

Significant LDNs were elicited in both conditions (see Table 2). Group differences in LDN amplitude (deviant minus standard) were addressed using a mixed design repeated measures ANOVA with factors Condition (phonemes, words), Electrode (F3, Fz, F4, inverted P9, inverted P10, inverted LM, inverted RM [inverted because of a polarity reversal]) and between subjects factor Group (controls, FRND, FRD children). The analysis yielded no main effects for Condition, but a main effect for Electrode was present (F(1.36,66.85) = 19.29, p < .001). Post hoc results indicate differences between frontal and parietal sites and RH and LH electrodes, specifically. Planned contrasts for comparing controls against familiar risk children yielded no significant effect. Planned contrasts for comparing fluent readers against FRD children, however, yielded an effect bordering significance (p = .06). Furthermore, no differences in LDN amplitude were found when comparing controls and
FRND children. Taken together, these results suggest a trend when comparing fluent and poor readers, irrespective of condition. No further main effects or interactions were found.

**Laterisation of LDN**

Scalp distributions are presented in Figure 3. Results of the phoneme condition for each participant group are presented in Figure 3(A). The scalp activity of the LDN looks similar across groups, with negative polarity on frontal electrodes and positive polarity around the mastoids. Scalp distributions of the word condition for each participant group are presented in Figure 3(B). The scalp activity of the LDN looks similar in all groups, and is similar to the activity in the phoneme condition: negative polarity can be observed on frontal electrodes and positive polarity around both mastoids.

We addressed potential differences in lateralization of phonemes versus words between groups. Since the previous analyses yielded a marginal effect of reading fluency and not of familial risk, and no differences between controls and FRND children, the following analysis was carried out with Fluent as a between-subjects factor. RH electrodes F4, P9 and RM were averaged, as well as LH electrodes F3, P9, and LM. A repeated measures ANOVA was run with within factors Condition (phonemes, words) and Hemisphere (LH, RH) with between subjects factor Fluent (fluent readers, poor readers). This yielded no main effect for Condition, but a significant main effect was found for Hemisphere ($F(1,50) = 9.40, p = .004$). Overall, LDN is larger in the LH. The absence of a main effect for Condition and the absence of an interaction effect between Hemisphere and Condition suggests that no differential processing of phonemes and words takes place, thus the LDN appears to be lateralized to the left hemisphere in both conditions. Lastly, a trend was found for Fluent, ($F(1,50) = 3.23, p = .078$)), indicating that the LDN tends to be larger in amplitude for fluent readers. No interaction effects were found. Specifically, an interaction Fluent*Hemisphere was absent, which indicates that both fluent and poor readers have a left lateralized LDN to speech processing.
Figure 1. ERP responses of the phoneme condition on electrodes Fz, F3, F4, P9, P10, RM and LM. Lines represent elicited ERPs for the standard (black, solid line), and deviant (red, dotted line) for control children ($N = 15$), the FRND group ($N = 22$) and the FRD group ($N = 15$). Control children are displayed in the left column, of the FRND children in the middle column and of the FRD children in the right column.
Figure 2. ERP responses of the word condition on electrodes Fz, F3, F4, P9, P10, RM and LM. Lines represent elicited ERPS for the standard (black, solid line), and deviant (red, dotted line) for control children \((N = 15)\), the FRND group \((N = 24)\) and the FRD group \((N = 15)\). Control children are displayed in the left column, of the FRND children in the middle column and of the FRD children in the right column.
Figure 3. Top, left, and right scalp distributions of the LDN response for phonemes and words displayed in voltage maps. (a) represents the scalp distributions of the phoneme condition, (b) shows the scalp distribution of the word condition. Scalp distributions of control children are displayed in the left column, of the FRND children in the middle column and of the FRD children in the right column. The time window represented is 510 to 590 ms in the phoneme condition, and 700 to 900 ms in the word condition.
Table 2

Mean LDN amplitude per electrode, per condition, per group

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Controls (n =15)</th>
<th>FRND (n =24)</th>
<th>FRD (n =15)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phonemes</td>
<td>Words</td>
<td>Phonemes</td>
</tr>
<tr>
<td>Fz</td>
<td>-1.01(1.76)*</td>
<td>-2.06(1.84)***</td>
<td>-1.16(1.15)***</td>
</tr>
<tr>
<td>F3</td>
<td>-.82(1.55)</td>
<td>-1.72(1.72)**</td>
<td>-1.29(.95)***</td>
</tr>
<tr>
<td>F4</td>
<td>-1.30(1.89)*</td>
<td>-2.21(2.06)***</td>
<td>-1.27(1.20)***</td>
</tr>
<tr>
<td>P9</td>
<td>-.04(1.61)</td>
<td>-.05(1.61)</td>
<td>.75(1.36)*</td>
</tr>
<tr>
<td>P10</td>
<td>.33(1.21)</td>
<td>.26(1.34)</td>
<td>-.37(1.17)</td>
</tr>
<tr>
<td>LM</td>
<td>-.21(1.44)</td>
<td>-.24(1.02)</td>
<td>-.84(1.33)**</td>
</tr>
<tr>
<td>RM</td>
<td>.30(1.17)</td>
<td>.42(1.15)</td>
<td>-.55(1.13)*</td>
</tr>
</tbody>
</table>

Note. Asterisks reflect LDN amplitudes to be significantly different from zero. Note: p < .05 *, p < .01 **, p < .001 ***.
**FR and reading status as predictors of overall LDN amplitude**

The relation between LDN amplitude and family risk and reading was further investigated by means of a hierarchical regression analysis. To this end, dummy variables were created, indicative of the reading status (fluent or dyslexic) and the FR status of the child. Because no effects of condition were found in the previous analyses, the total LDN amplitude was averaged over conditions and electrodes. Following, a hierarchical regression analysis with LDN amplitude as a dependent variable was carried out, with the predictors FR status entered in step 1, and reading status entered in step 2.

Table 3

Hierarchical regression analysis with dependent variable LDN amplitude

<table>
<thead>
<tr>
<th>Predictor</th>
<th>$\Delta R^2$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>FR</td>
<td>- .01</td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td>.10*</td>
<td></td>
</tr>
<tr>
<td>FR</td>
<td>- .14</td>
<td></td>
</tr>
<tr>
<td>Dys</td>
<td>- .34*</td>
<td></td>
</tr>
</tbody>
</table>

Note. * $p < .05$

Results indicate that reading status significantly predicts LDN amplitude, but not FR.

**Discussion**

We investigated pre-attentive processing of natural speech phonemes and words in poor and fluent readers at risk for dyslexia and fluently reading controls, to tease apart its relation with reading directly versus its relation with familial risk for dyslexia. No clear MMN could be identified in our waveforms, neither in the phoneme- nor in the word condition. However, we did observe clear LDNs in both conditions. The results of contrast analyses show a trend towards FRD children having attenuated processing of both
phonemes and words compared to fluent readers, who have a marginally higher LDN amplitude. These results gain further support by the finding that reading status, but not FR status, is predictive of LDN amplitude. Moreover, the LDN amplitude of controls and FRND children did not differ. Reading status is thus predictive of LDN amplitude when processing both less complex information such as a phoneme contrast, and more complex lexical items such as an inflected verb. These results suggest that deficits in pre-attentive speech processing are not related to familial risk for dyslexia, but to reading fluency specifically. The choice for a paradigm targeting pre-attentive processing diminishes the possibility that the outcomes regarding speech processing were confounded by attention.

Our results regarding the FRD group are in line with other studies that have looked into speech processing on phoneme or syllable level. Schulte-Körne et al. (1998) found that dyslexic children did not have an LDN to speech processing compared to controls, and Lachmann et al. (2005) show that poor readers have no MMN to syllable changes. Meng et al. (2005) found an attenuated MMN to speech processing in Chinese children with dyslexia, both in phoneme and lexical-syllabic context. However, our results contrast with those of Neuhoff et al. (2012). They looked into differences between dyslexic participants and their unaffected siblings at age 12 and found the LDN to be attenuated in both familial risk groups. In our study, we found lower LDN amplitudes to be associated with reading status, not FR. Possibly, the incongruent outcomes can be attributed to methodological differences. The stimuli used in the German study were not natural speech vowels or lexical items carrying grammatical information, but synthesized CV syllables /ba/ and /da/. A study by Blomert and Mitterer (2004) demonstrated that poor readers are worse at a categorization task when the stimuli are comprised of synthesized speech items versus natural speech items, which could explain the differential findings.

No differences were found in lateralization between the phoneme and word condition: the LDN was not more left lateralized in the word condition than in phoneme condition. Both types of speech stimuli seemed to elicit a clear left lateralized LDN, though we had expected the grammatical change in the word condition to elicit a stronger left lateralized response (see Shtyrov et al., 2005). Possibly, as previously suggested by Shtyrov and colleagues (2005), the absence of laterality differences between conditions could be explained by familiarity: if the listener is familiar with the (pronunciation of) the stimuli, left lateralization for these items will occur. This idea is supported by their finding that processing of nonwords was less lateralized (Shtyrov et al., 2005). Similarly to Schulte-
Körne et al. (2001), we did not find any differences in lateralization between poor and fluent readers. Our findings are not in line with previous studies that have reported differential hemispheric activation in dyslexic participants (Kujala et al., 2003; Lovio et al., 2010; Lyytinen et al., 2005; van Herten et al., 2008; van Zuijen et al., 2013). However, the general finding that speech processing is left lateralized, is in line with the idea that language functions are dominant in the left hemisphere (Dehaene et al., 1997).

The outcomes of the current study are in close relation with outcomes of a DDP study by Van Zuijen et al. (2013). Similar patterns of speech processing were observed: 2 month old infants who would later be poor readers had an attenuated MMN compared to control children and FRND children. It thus seems that for poor readers, deficits in speech processing are visible in early development. Reading status is predictive of the LDN amplitude as observed in early adolescence, suggesting the deficit to persist. Furthermore, our results are interesting in light of previous DDP studies looking into basic auditory processing (Plakas et al., 2013; Hakvoort et al., 2015). These studies show that basic auditory processing is impeded in both FRD and FRND children. Therefore, deficits in basic auditory processing are considered correlates of being at risk for dyslexia (Plakas et al., 2013; Hakvoort et al., 2015). Processing of acoustically more complex and qualitatively different information like speech, however, seems to be specifically related to reading ability and not to being at risk for dyslexia. Participants in the study by Hakvoort and colleagues (2015) were the same as the ones in the current study. However, to draw a firmer conclusion about basic auditory processing versus speech processing, both paradigms would have to be addressed in the same groups in one analysis.

**Conclusion**

The current study investigated speech processing in familial risk children with and without reading problems and controls. Reading status, not FR, significantly predicts LDN amplitude of speech processing. Both poor- and fluent readers show a predominantly left lateralized LDN to speech stimuli. Attenuated speech processing can be seen as a factor that directly relates to poor reading ability, and not to being at familial risk for dyslexia.