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Deviant neurophysiological responses to phonological regularities in speech in dyslexic children

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Abstract

Developmental dyslexia is strongly associated with a phonological deficit. Yet, implicit phonological processing (in)capacities in dyslexia remain relatively unexplored. Here we use a neurophysiological response sensitive to experience-dependent auditory memory traces, the mismatch negativity (MMN), to investigate implicit phonological processing of natural speech in dyslexic and normally reading children. In a modified passive oddball design that minimizes the contribution of acoustic processes, we presented non-words that differed by the degree of phonotactic probability, i.e. the distributional frequency of phoneme combinations in a given language. Overall morphology of ERP responses to the non-words indicated comparable processing of acoustic–phonetic stimulus differences in both children groups. Consistent with previous findings in adults, normally reading children showed a significantly stronger MMN response to the non-word with high phonotactic probability (*notsel*) as compared to the non-word with low phonotactic probability (*notkel*), suggesting auditory cortical tuning to statistical regularities of phoneme combinations. In contrast, dyslexic children did not show this sensitivity to phonotactic probability. These findings indicate that the phonological problems often reported in dyslexia relate to a subtle deficit in the implicit phonetic–phonological processing of natural speech.

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Keywords: Developmental dyslexia; ERP; Mismatch negativity; Phonological deficit; Phonotactic probability

1. Introduction

The efficient processing and representation of speech sounds, phonological skills, constitutes a common bottleneck to fluent reading (National Research Council, 1998). In particular, numerous studies indicate that the failure to adequately develop phonological skills may underlie reading problems such as those experienced in developmental dyslexia (Snowling & Hulme, 2005). Developmental dyslexia is a specific reading disorder that is characterized by difficulties in reading, spelling, or both that are unexpected in relation to age and other cognitive abilities (Lyon, 1995). It affects a relatively large percentage of the population with prevalence estimates in Western countries ranging from 4 to 9 percent (Germany: Esser, 1990; United States of America: Katusic, Colligan, Barbaresi, Schaid, & Jacobsen,

2001; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). A recent nationwide study of an elementary school population of 150,000 children in The Netherlands estimated a prevalence of reading, spelling, or both problems of 9 percent, and a prevalence of developmental dyslexia of 4 percent (Blomert, 2005). Poor phonological skills form a core deficit in dyslexia, although they may sometimes be accompanied by additional sensory deficits in the auditory, visual, or both domains (Ramus et al., 2003; Stein & Walsh, 1997).

Phonological difficulties in individuals with dyslexia are apparent from poor behavioural performance on phonological tasks involving phonological awareness (phoneme deletion, rhyme judgments) or verbal memory (Howes, Bigler, Lawson, & Burlingame, 1999; O'Neill & Douglas, 1991; Tijms, 2004). Furthermore, during performance of such tasks dyslexic individuals show abnormal patterns of brain activation, with a typical dysfunction in left temporo-parietal regions as revealed by hemodynamic brain imaging studies, and neural time course differences as shown by studies using electroencephalography (EEG) or magnetoencephalography (MEG) (for reviews see McCandliss & Noble, 2003; Temple, 2002). These deviant

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brain responses in dyslexic individuals reflect their difficulties with explicit phonological tasks. However, explicit phonological tasks entail processing demands over and above language processes, for example, high attention and memory loads. Such task-related cognitive requirements may alter the way in which phonological information is usually processed under normal perceptual conditions (Hickok & Poeppel, 2004). As a consequence, explicit phonological tasks do not necessarily reveal subtle underlying anomalies in the phonological processing of speech.

Event-related potential (ERP) measures of implicit phonological processing are particularly suited to explore on-line phonological processing (in)capacities in dyslexic children. A recent investigation of phonological priming effects on ERP responses to spoken words and non-words revealed selective processing anomalies in dyslexic children at a prelexical phonetic–phonological level, along with normal processing at a phonological–lexical level (Bonte & Blomert, 2004). The present study utilizes ERP correlates of implicit processing of phonological regularities in speech to further investigate these phonetic–phonological anomalies. We focus on a phonological regularity that starts to influence spoken language acquisition during the first year of life (Jusczyk, 1999; Saffran, Aslin, & Newport, 1996) and continues to influence speech processing across the life-span (Auer & Luce, 2005), that is, phonotactic probability. Phonotactic probability corresponds to the distributional frequency of phonemes and phoneme sequences in the syllables and words of a given language (Trask, 1996). During normal development, the neural system underlying speech perception may become finely tuned to these distributional properties of the language input which thereby facilitate the acquisition, recognition and representation of spoken language (Auer & Luce, 2005).

We employed an automatic ERP response associated with mnemonic functions of the auditory association cortex, the mismatch negativity (MMN) (Näätänen, 2001; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001; Picton, Alain, Otten, Ritter, & Achim, 2000). The MMN is typically measured in an oddball paradigm in which the response is automatically elicited by an infrequently occurring discriminable change (infrequent deviant stimulus or oddball) in a repetitive aspect of auditory stimulation (frequent standard stimuli). The size, latency and topographical distribution of this change detection response may reflect the properties of auditory memory traces activated by the standard and deviant stimuli (Näätänen et al., 2001; Picton et al., 2000).

The MMN elicited by speech has been shown to reflect both acoustic change detection and phoneme-specific processes (Näätänen, 2001; Winkler et al., 1999). Important evidence for the existence of phoneme-specific processes was obtained in a cross-linguistic oddball study using the Finnish/Estonian vowel /e/ as the standard stimulus and the Finnish/Estonian vowel /ö/, and the Estonian vowel /õ/ as deviant stimuli (Näätänen et al., 1997). In this study, Finnish subjects showed a significantly larger MMN response to the deviant Finnish/Estonian vowel /ö/ than to the deviant Estonian vowel /õ/, even though the acoustic deviation from the standard /e/ was smaller for the

Finnish/Estonian /ö/ than for the Estonian /õ/. In contrast, Estonians showed equally large MMN responses to both deviant vowel stimuli. Enhanced MMN responses to phonemes that are prototypical in the perceiver's native language are also reported in other studies and have been suggested to reflect the existence of permanent phoneme traces in the auditory cortex (Cheour et al., 1998; Dehaene-Lambertz, 1997; Dehaene-Lambertz & Baillet, 1998; Näätänen, 2001; Näätänen et al., 1997).

In a recent study with Dutch adults, non-words with a high phonotactic probability (HPP) in Dutch were also found to elicit significantly stronger MMN responses than non-words with a low phonotactic probability (LPP) in Dutch (Bonte, Mitterer, Zellagui, Poelmans, & Blomert, 2005). This MMN enhancement was observed for the HPP non-word *notsel* as compared to the LPP non-word *notkel*, and replicated with a non-word pair with a comparable difference in phonotactic probability, but a smaller acoustic difference: *notsel* (HPP) versus *notfel* (LPP). Importantly, MMN responses did not show any significant differences in a third, acoustic control, experiment with stimuli having comparable phonotactic probability (*so* vs. *fo*). These findings thus suggest that phoneme-specific processes underlying the MMN are influenced by statistical regularities of speech sound combinations in the language environment.

Here we use the same paradigm to study implicit processing of phonological regularities in normally reading and dyslexic children. Our paradigm was specifically constructed to minimize the contribution of acoustic processes and to study relatively high-level phonological processes (Bonte et al., 2005; Eulitz & Lahiri, 2004). The HPP non-word *notsel* and the LPP non-word *notkel* were both presented as standards and deviants in a reversed oddball design. This non-word pair was selected because it involves a clear phonetic contrast (/s/ fricative vs. /k/ stop consonant) for which no auditory discrimination problems have been reported in individuals with dyslexia (Adlard & Hazan, 1998; Mody, Studdert-Kennedy, & Brady, 1997). MMN difference waves were derived from the ERP activity elicited by the same non-word presented as standard and deviant in separate experimental blocks. This enabled us to estimate auditory cortical (MMN) correlates of variation in phonotactic probability independent of differences in ERP morphology due to acoustic–phonetic stimulus differences per se. Importantly, our experimental design allowed us to study both these more general differences in ERP morphology due to auditory stimulation and specific phonological MMN effects.

The clear phonetic contrast between our stimuli was expected to similarly influence general ERP morphology in normally reading and dyslexic children. Furthermore, in normally reading children we expected a similar neurophysiological sensitivity to phonotactic probability as previously found in adults: an enhanced MMN response to non-words with a high versus low phonotactic probability (Bonte et al., 2005). The presence or absence of comparable neurophysiological change detection responses in dyslexic children may indicate whether they exhibit subtle deficits during the implicit phonological processing of meaningless speech.

Table 1
Descriptive data for normal readers and dyslexic children

	Normal readers (<i>n</i> = 14)	Dyslexic children (<i>n</i> = 12)	Differences
Age (years)	8.2 (7.1–9.5)	9.5 (8.1–11.3)	$t = -3.6, p < .005$
IQ ^a	109 (90–30)	106 (90–126)	
Word reading ^b	6.1 (1.8)	2.6 (2.1)	$t = 4.6, p < .001$
Non-word reading ^b	5.9 (1.5)	3.0 (1.7)	$t = 4.7, p < .001$
Vocabulary ^b	5.8 (1.1)	6.3 (1.7)	$t = -1.0, ns$
Phoneme deletion ^c	88 percent (8 percent)	78 percent (15 percent)	$t = 2.1, p < .05$

Age, IQ scores (mean (range)) and performance on language tests (mean (*SD*)).

^a All children showed normal or above normal IQ scores.

^b Age-appropriate norms (standardized scale; mean = 5, *SD* = 2).

^c Percentage correct.

2. Materials and methods

2.1. Subjects

Thirty subjects (15 dyslexic, 15 normally reading) participated in the present study. Data of 26 subjects were included in the analysis, including 12 dyslexic children (5 f; mean age: 9.5 ± 1.1 years) and 14 normal readers (9 f; mean age: 8.2 ± 0.7 years). Data of three dyslexic children and one normal reader were discarded due to excessive movement artefacts.

All children were given a present for participation. Informed consent was obtained from the parents of the children. Approval for the study was granted by the Ethical Committee of the Faculty of Psychology at the University of Maastricht. Dyslexic children were recruited from the Regional Institute of Dyslexia (RID), which is one of the major specialized dyslexia institutes in The Netherlands. Prior to the present study, they were diagnosed as dyslexic after an extensive cognitive psycho-diagnostic procedure by the RID. This testing procedure included an intelligence test (WISC-R, Dutch version; WISC-R project group, 1986), the results of which were used in the present study. Each of the dyslexic children met the following diagnostic criteria: evidence of a significant impairment in reading that cannot be attributed to general learning problems, co-morbid cognitive or behavioural disorders such as attention deficit hyperactivity disorder, or insufficient education. Normal readers were recruited from local schools, and were judged by their school teachers to be average or above average in academic achievement.

All subjects were native Dutch speakers. Three dyslexic children were left-handed and all other subjects were right-handed as assessed with Annett's Handedness Questionnaire (Annett, 1979). All parents of children reported the absence of any history of hearing loss. Subject characteristics and results of behavioural tests are given in Table 1. Dyslexic children were on average 1.3 year older than normal readers. For practical reasons, including the availability of test materials and time constraints, different standardized metrics were used for IQ assessment in dyslexic children (WISC-R; WISC-R project group, 1986) and normal readers (Raven Colored Progressive Matrices; Raven, Raven, & Court, 1998). Both metrics provide reliable standardized IQ-scores and every child in the study scored at or above normal on their respective test (see Table 1). All children performed standardized language tests, including two reading tests, the Eén-minuut-leestest (1-min-reading test, Brus & Voeten, 1999) and a non-word reading test (Van den Bos, Iutje Spelberg, Scheepsmma, & de Vries, 1999), an active vocabulary test (subtest of WISC-R, WISC-R project group, 1986), and additionally, an unpublished phoneme deletion task (devised by the RID). The phoneme deletion test asks participants to delete the first phoneme of an auditorily presented word and to pronounce the remaining word. On the reading tests, dyslexic children performed significantly worse than normal readers, who scored at an age-appropriate level. Dyslexic and normally reading children did not differ in vocabulary skills. Performance on the phoneme deletion test showed weak phonological skills in each of the dyslexic children.

2.2. Stimuli and task

Stimuli were two bisyllabic non-words, one with high phonotactic probability (HPP: *notsel* [nɔtsɛl]), and the other with low phonotactic probability

(LPP: *notkel* [nɔtkɛl]). These non-words are phonotactically legal in Dutch and the stress was on the first syllable, the default stress in Dutch. Table 2 gives the phonotactic probabilities of our stimuli as determined by counts of phoneme sequences weighted for word frequency in a Dutch word form database (CELEX corpus, Baayen, Piepenbrock, & Gulikers, 1995). As can be seen in Table 2, the probabilities of the individual phonemes, that is /s/ and /k/ alone, are similar. However, the consonant cluster /ts/ has a higher phonotactic probability than /tk/. The relative difference in phonotactic probability between the stimuli is further increased by the vowels /o/ and /e/ that precede and follow the consonant clusters. Importantly, no Dutch word starts with the phoneme sequence /nots/ or /notk/, or contains the phoneme sequences /notsel/ or /notkel/, thus making top-down lexical effects unlikely.

Stimuli were spoken by a female native Dutch speaker and recorded at a sampling rate of 44.01 kHz on a DAT recorder. The digitized stimuli were D/A converted with a 16-bit resolution, bandpass filtered (100 Hz–10.5 kHz), resampled at 22.05 kHz, and edited with Praat software (Boersma & Weenink, 2002). Editing included matching for loudness by equating the maximal amplitude to 95 percent of the dynamic range, which resulted in equal rms amplitudes for the stimuli. Stimulus length was equated to 550 ms (original range: 480–600 ms) using PSOLA (140–280 Hz as extrema of the F0 contour). We carefully checked our stimuli for possible alterations in F0 after length equation and did not find any detectable changes. To minimize the likelihood that the MMN would be determined by only one or a few particular acoustic features, we used four utterances of each non-word stimulus (see also Eulitz & Lahiri, 2004; Jacobsen, Schröger, & Alter, 2004). Fig. 1 illustrates that both sets of non-word utterances showed comparable variation in pitch and intensity. Acoustic differences between the two non-words started around 160 ms after stimulus onset, at the stimulus medial consonant clusters /ts/ and /tk/. The onset of stimulus deviation is approximate because we used multiple utterances of natural speech stimuli. The preceding vowel /o/ did not show systematic differences between our non-word stimuli.

During the experiment, children watched a silent movie while the stimuli were presented binaurally through loudspeakers at 65 dB SPL. Stimuli were presented with an inter-stimulus interval of 650 ms. There were four experimental blocks with 600 stimuli each. In two of these blocks, the HPP non-word served as standard (84 percent) and the LPP non-word as deviant (16 percent), in the other two blocks standards and deviants were reversed, i.e. the LPP non-word

Table 2
Frequency counts of phonemes and phoneme combinations in our non-word stimuli (log-transformed)

	cvccvc	cvc[c]vc	cv[cc]vc	c[vcc]vc	cv[ccv]c	c[vccv]c	[cvccvc]
Notsel	6.50	5.83	4.32	4.59	3.99	–	
Notkel	6.45	4.51	2.53	0.95	–	–	

Frequency counts were weighted for word frequency and based on the Celex corpus with 42 million Dutch words (Baayen et al., 1995). [...] indicates the phoneme(s) for which counts are given, c = consonant, v = vowel. For example, the third column: cv[cc]vc, gives frequency counts for /ts/ and /tk/ respectively. The frequency counts of the single phonemes /s/ and /k/ in the second column only include syllable-initial occurrences. “–” indicates a frequency of 0.

Fig. 1. Pitch and intensity contours of the non-word stimuli used in the experiment: *notsel* [nɒtsəl] and *notkel* [nɒtkəl], which have a high versus low phonotactic probability. We used four utterances of each non-word.

was the standard and the HPP non-word the deviant. The order of experimental blocks was counterbalanced between subjects. In total, 1008 standards and 192 deviants were presented for each non-word.

2.3. EEG recording and analysis

EEG data were recorded (0.01–50 Hz, sampling rate 250 Hz) in a sound-attenuating and electrically shielded room from 30 electrode positions (Extended International 10–20 System, Nuwer et al., 1998) relative to a nose reference. Eye-movements and blinks were measured with bipolar VEOG/HEOG channels. All electrode impedance levels (EEG and EOG) were kept below 5 k Ω . The raw EEG data were 1–30 Hz bandpass filtered and corrected for blink artefacts (Semlitsch, Anderer, Schuster, & Presslich, 1986). Subsequently, EEG data were epoched from –100 to 850 ms relative to stimulus onset and baseline corrected (100 ms pre-stimulus interval). Epochs containing data exceeding a maximum voltage criterion of 100 μ V were rejected. Standards immediately following deviants were not included in the analysis. The mean (SD) number of accepted epochs in normally reading and dyslexic children were respectively, 147 (14) and 152 (13) for HPP deviants, 144 (17) and 152 (13) for LPP deviants, 613 (60) and 640 (62) for HPP standards and 626 (59) and 653 (53) for LPP standards.

Statistical analyses were performed on the central electrode Cz, where MMN responses were clearly detectable. We first analyzed the strength and timing of ERP activity elicited by the frequently presented standard stimuli using a repeated-measures ANOVA with *phonotactic probability* (HPP vs. LPP) as the ‘within subjects’ factor and *group* (normal readers vs. dyslexic children) as the ‘between subjects’ factor. We subsequently analyzed activity elicited by standard and deviant non-word stimuli using a repeated-measures ANOVA with *stimulus type* (standard vs. deviant) and *phonotactic probability* (HPP vs. LPP) as ‘within subjects’ factors and *group* (normal readers vs. dyslexic children) as the ‘between subjects’ factor. Timing of ERP responses was measured by determining individual peak latencies in the 90–200 ms window (“P1”), 250–350 ms window (“N2”) and 450–550 ms window (“N4”). Amplitude measures included both individual peak amplitudes and mean amplitude taken from the 50 ms window around the individual peak latency.

Mismatch effects were further examined with deviant-standard difference waveforms that were calculated separately for each non-word across blocks, for example *notsel* as deviant minus *notsel* as standard. From these difference waves we calculated timing and amplitude parameters of mismatch responses that were tested using repeated-measures ANOVA with *phonotactic probability* (HPP vs. LPP) as the ‘within subjects’ factor and *group* (normal readers vs. dyslexic children) as the ‘between subjects’ factor. MMN peak latency was determined for each individual subject in the time window between 360 and 580 ms after stimulus onset (~200–420 ms after auditory stimulus deviation). MMN amplitude measures included both individual peak amplitude and mean amplitude taken from the 50 ms window around the individual MMN peak latencies. To investi-

gate correlations between MMN measures and language skills, age and IQ, we computed Pearson’s correlation coefficients.

3. Results

3.1. ERP morphology

Fig. 2A illustrates the mean time course of ERP activity elicited by the non-words *notsel* (HPP) and *notkel* (LPP). Non-words elicited a very similar sequence of activity in normally reading and dyslexic children, which was characterized by a broad positivity peaking around 150 ms followed by two negative responses peaking around 290 and 510 ms after stimulus onset. We will refer to the positivity as P1 and the negativities as N2 and N4.

Fig. 2B shows the mean difference waves of the ERP activity evoked by the frequently presented standards of the two non-words (*notsel*–*notkel*), indicating that there was stronger activation for *notsel* than *notkel* in the N2 and N4 windows. The time course and amplitudes of these stimulus related differences were similar in normally reading and dyslexic children.

Amplitude and latency characteristics of the N2 and N4 responses to standards were analyzed at electrode Cz using a repeated-measures ANOVA with *phonotactic probability* as the ‘within subjects’ factor and subject group as the ‘between subjects’ factor. In both normally reading and dyslexic children, *notsel* elicited significantly stronger N2 and N4 responses than *notkel* as indicated by main effects of *phonotactic probability* for the peak amplitudes of the N2 ($F(1,24) = 5.0, p < .05$) and the N4 ($F(1,24) = 5.7, p < .05$). The same analysis of mean amplitude in 50 ms time windows around the individual N2 and N4 peaks corroborated these findings (main effects of *phonotactic probability* $F(1,24) = 4.3, p < .05$ and $F(1,24) = 4.1, p < .05$). N2 and N4 amplitudes were similar in both subject groups (no main effects of group). Peak latencies of the N2 and N4 were very similar for both non-words and both subject groups and did not show any significant effects.

The same statistical analysis of amplitude and latency characteristics in the preceding P1 window did not lead to any

Fig. 2. ERP activity elicited by *notsel* and *notkel* for both normally reading and dyslexic children. (A) Grand average ERPs elicited by standards of both non-word stimuli. (B) ERP difference waves (*notsel*–*notkel*) indicating enhanced ERP responses for *notsel* versus *notkel* in both subject groups. Note that auditory stimulus deviation occurred ~160 ms after stimulus onset.

significant effects of phonotactic probability. However, on average normally reading children showed larger P1 responses than dyslexic children as indicated by significant main effects of group for P1 peak amplitude ($F(1,24)=4.4$; $p<.05$) and mean amplitude ($F(1,24)=4.9$; $p<.05$). Inspection of individual subject data suggests that this group difference resulted from age-related inter-subject variability in P1(N1) morphology. Thus, in the majority of children early ERP activity elicited at frontocentral electrodes was characterized by a broad P1 peaking around 150 ms, followed by a negative response peaking around 290 (“N2”), resembling the P1–N2 complex which typically dominates auditory ERPs in children up to about 10 years of age (Bruneau & Gomot, 1998; Cepenine, Rinne, & Näätänen, 2002; Csépe, 1995; Takeshita et al., 2002). Interestingly, some of the older children, and in particular the four oldest children (10–11 years; all dyslexic), not only showed P1 and N2 responses but also a superimposed negativity around 150 ms. This additional negativity most likely reflects a precursor of the adult N1 peak and attenuated the grand average P1 response

in dyslexic children (see flat part of the grand average P1 in Fig. 2).

3.2. MMN findings

The main goal of the present study was to investigate whether ERP mismatch responses to non-words with a high (HPP) versus low (LPP) phonotactic probability would indicate a similar sensitivity to phonotactic probability in normally reading and dyslexic children. To get an overall impression of ERP activity elicited by standard and deviant stimuli we first analyzed P1, N2 and N4 amplitude and latency values at Cz using a two (stimulus type) $\times$ two (phonotactic probability) repeated-measures ANOVA with subject group as the ‘between subjects’ factor. The P1 and N2 responses did not show significant differences between standard and deviant stimuli. However, in both subject groups, deviant stimuli did elicit a stronger N4 response than standard stimuli (main effects of stimulus type for N4 peak amplitude $F(1,24)=19.9$, $p<.001$ and mean N4 amplitude $F(1,24)=12.3$, $p<.005$). Furthermore, in normally reading and dyslexic children this mismatch effect was differentially influenced by phonotactic probability, as indicated by stimulus type-by-phonotactic probability-by-group interactions for N4 peak amplitude $F(1,24)=6.1$, $p<.025$, and mean N4 amplitude $F(1,24)=7.4$, $p<.025$. N4 amplitude measures did not show a main effect of group and N4 latency did not show any significant effect. Mismatch effects were further tested by examining latency and amplitude characteristics of deviant-standard difference waves determined separately for each non-word across blocks, for example *notsel* as deviant minus *notsel* as standard.

Fig. 3 illustrates the grand average ERP waveforms and difference waves for *notsel* (HPP) and *notkel* (LPP). As can be seen in this figure, in normal readers, *notsel* (HPP) deviants elicited a clear MMN at ~500 ms after stimulus onset (~340 after auditory stimulus deviation), whereas *notkel* (LPP) deviants lead to a smaller MMN response around the same latency. In contrast, dyslexic children did not show a stronger MMN to the HPP than to the LPP non-word (Fig. 3). In fact, whereas *notsel* deviants did not elicit a clear MMN response, *notkel* deviants lead to a strong MMN response around 500 ms.

To test these observations we performed repeated-measures ANOVAs with phonotactic probability as the ‘within-subjects’ and group as the ‘between-subjects’ factor on individually determined MMN latency and amplitude measures recorded at Cz (Table 3). This individual analysis confirmed the occurrence of mismatch responses at around 500 ms after stimulus onset (~340 after auditory stimulus deviation), with no significant latency differences between *notsel* and *notkel* or subject groups. MMN peak latencies showed a large variability between subjects (Table 3). Because of this latency variability, in all conditions and both subject groups, the grand average difference waveforms (Fig. 3) suggest smaller negative activity than the individually determined peak and mean amplitude measures (Fig. 4; Table 3).

Analysis of MMN amplitude measures led to significant phonotactic probability-by-group interactions for peak amplitude ($F(1,24)=12.2$, $p<.005$) and mean amplitude

Fig. 3. ERP activity elicited by standard and deviant stimuli for both normally reading and dyslexic children. (A) Grand average ERPs elicited by standard and deviant stimuli indicating mismatch effects for HPP and LPP non-words. (B) ERP difference waveforms of normally reading and dyslexic children for HPP (notsel deviant–notsel standard) and LPP (notkel deviant–notkel standard) non-words. Note that auditory stimulus deviation occurred ~ 160 ms after stimulus onset.

($F(1,24) = 10.5, p < .005$), without any main effects of group or phonotactic probability. In normally reading children the HPP non-word *notsel* elicited a significantly stronger MMN than the LPP non-word *notkel*, as indicated by post hoc t -tests of MMN peak amplitude ($t(1,13) = -3.0, p < .01$) and MMN mean

amplitude ($t(1,13) = -2.2, p < .05$). In contrast, dyslexic children showed a stronger MMN to the LPP non-word *notkel* than to the HPP non-word *notsel*, leading to an almost significant effect for MMN peak amplitude ($t(1,11) = -2.0, p = .07$) and a significant effect for MMN mean amplitude ($t(1,11) = -2.6, p < .05$). In

Table 3
Mean (range) latency and amplitude characteristics of MMN activity in normally reading and dyslexic children

	Peak latency (ms)	Peak amplitude (μV)	Mean amplitude (μV)
Normal readers			
Notsel (HPP)	499 (392–580)	-2.65 (-0.9 to -4.4)	-2.06 (-0.5 to -4.0)
Notkel (LPP)	496 (416–560)	-1.56 (-0.3 to -2.8)	-1.07 (-0.1 to -2.7)
t ($df = 13$)	0.1	-3.0**	-2.2*
Dyslexic children			
Notsel (HPP)	488 (396–576)	-1.71 (0.2 to -3.2)	-0.94 (0.6 to -2.0)
Notkel (LPP)	485 (392–564)	-2.64 (-0.8 to -4.6)	-1.90 (-0.2 to -3.7)
t ($df = 11$)	0.1	2.0	2.6*

Peak latency, peak amplitude and mean amplitude (50 ms window around the peak latency) were determined individually for each subject. * $p < .05$, ** $p < .01$.

Fig. 4. Mean (SEM) latency and amplitude measures of MMN activity in normal readers and dyslexic children. Peak latency and mean amplitude (50 ms window around the peak latency) were determined individually for each subject. Error bars represent standard error of the mean. Asterisks indicate significant differences between conditions (post hoc *t* comparisons).

order to test the presence of similar group differences in effects of phonotactic probability on a more extended set of electrodes, we further analyzed MMN amplitude and latency measures at electrodes Fz, Pz, C3, C4, T3 and T4. As illustrated in Fig. 4, these analyses confirmed the presence of an enhanced MMN response to the HPP non-word *notsel* in normal readers and the opposite effect, a larger MMN response to the LPP non-word *notkel*, in dyslexic children.

3.3. Correlations with behavioural measures

The extent to which *notsel* (HPP) elicited stronger MMN activity than *notkel* (LPP) may reflect subjects' neurophysiological sensitivity to the phonotactic probability of phoneme sequences. To further investigate the phonological nature of this neurophysiological measure we examined whether it was correlated with subjects' phonological skills as measured with the non-word reading test (phonological decoding) and phoneme deletion test (phonological awareness). For each of the normally reading and dyslexic children the sensitivity to phonotactic probability was estimated from individual difference scores (*notsel*–*notkel*) of MMN peak amplitude, mean amplitude and peak latency. We computed correlations between these individual MMN difference scores and age, IQ, word reading, non-word reading, vocabulary and phoneme deletion skills. As shown in Table 4, this analysis revealed significant correlations between MMN difference scores of peak amplitude and non-word reading ($r(n=26) = -.47, p < .025$), and mean amplitude and non-word reading ($r(n=26) = -.47, p < .025$; see also Fig. 5). Additionally, amplitude measures tended to correlate with performance on the phoneme deletion test (mean amplitude $r(n=26) = -.36, p = .07$), and with word reading (peak amplitude $r(n=26) = -.37, p = .06$; mean amplitude $r(n=26) = -.38,$

Table 4

Pearson's correlations between MMN difference scores (*notsel*–*notkel*) of latency, peak amplitude and mean amplitude (50 ms window around the peak latency), and age, IQ and behavioural measures for all subjects

	Latency	Peak amplitude	Mean amplitude
Age (years)	–0.07	0.32	0.33
IQ	0.07	0.16	0.28
Word reading ^a	0.06	–0.37, $p = .06$	–0.38, $p = .05$
Non-word reading ^a	–0.01	–0.47*	–0.47*
Vocabulary ^a	–0.02	0.17	0.18
Phoneme deletion ^b	0.12	–0.31	–0.36, $p = .07$

* $p < .05$.

^a Age-appropriate norms (standardized scale; mean = 5, $SD = 2$).

^b Percentage correct.

$p = .053$). As indicated by these negative correlations, children with better phonological (and reading) skills showed a larger MMN enhancement for *notsel* (HPP) as compared to *notkel* (LPP). Within-group correlations did not reach statistical significance. As illustrated in Fig. 5, the significant negative correlation between MMN amplitude difference scores (*notsel*–*notkel*) and non-word reading scores was at least partly driven by the normal readers who followed the overall trend (mean amplitude: $r(n=14) = -.31, ns$; peak amplitude: $r(n=14) = -.15, ns$). Within the dyslexic group correlations were less clear (mean amplitude: $r(n=12) = .11, ns$; peak amplitude: $r(n=12) = -.10, ns$). There were no significant correlations between MMN difference scores and any of the other behavioural measures, age or IQ.

4. Discussion

We investigated implicit phonological processing of meaningless speech in normally reading and dyslexic children by

Fig. 5. Correlation between non-word reading scores and individual MMN mean amplitude difference scores (notsel–notkel) for normally reading (grey circles) and dyslexic children (black circles).

comparing neurophysiological mismatch responses to non-words with a high (HPP) versus low (LPP) phonotactic probability, *notsel* and *notkel*. Both non-words elicited a comparable sequence of ERP responses in normally reading and dyslexic children. Furthermore, both subject groups showed similarly enhanced N2 and N4 responses to *notsel* as compared to *notkel* stimuli. The analysis of mismatch responses for HPP (notsel deviant–notsel standard) versus LPP (notkel deviant–notkel standard) non-words indicated a clearly enhanced MMN response for the HPP non-word in normally reading children, analogous to previous findings in adults (Bonte et al., 2005). In contrast, ERP activity of dyslexic children did not reflect this sensitivity to phonotactic probability, and even showed the opposite pattern of an enhanced MMN response for the LPP non-word, supporting the idea of a subtle deficit in the implicit phonetic–phonological processing of natural speech (Bonte & Blomert, 2004). Furthermore, our neurophysiological measure of subjects' sensitivity to variations in phonotactic probability (notsel–notkel difference scores of MMN amplitude) correlated significantly with behavioural measures of phonological skills. That is, children with better phonological decoding skills (non-word reading) showed a larger MMN enhancement for *notsel* (HPP) as compared to *notkel* (LPP). Although within group correlations did not reach significance, the effect seemed to be somewhat larger in the normal readers.

The general sequence of ERP activity elicited by non-words was similar in normally reading and dyslexic children and was characterized by a broad positivity peaking around 150 ms, followed by two negative responses peaking around 290 (“N2”) and 510 ms (“N4”) after stimulus onset. The broad positivity and the first negativity “N2” resemble the P1–N2 (sometimes called P1–N250) complex which dominates the auditory obligatory ERPs in children up to about 10 years of age (Bruneau & Gomot, 1998; Ceponiene et al., 2002; Csépe, 1995; Takeshita et al., 2002). ERP activity in the P1–N2 window shows substantial structural and functional changes with age and probably

reflects auditory sensory processing until efficient adult cortical networks are established (Ceponiene et al., 2002; Takeshita et al., 2002). Interestingly, some of these morphological changes were reflected in the ERP data of the older children (10–11 years, all dyslexic). That is, these children not only showed P1 and N2 responses but also an additional negativity around 150 ms, indicative of a precursor of the adult N1, leading to an attenuated P1 response in the dyslexic group. Activity in the “N4” window, in which also the MMN responses occurred, probably reflects continued processing of complex natural speech stimuli like the bisyllabic non-words used in the present experiment. Importantly, morphological differences in ERP activity elicited by our two non-word stimuli, i.e. stronger N2 and N4 responses for *notsel* than *notkel*, were identical in both subject groups, indicating comparable neurophysiological processing of acoustic–phonetic stimulus differences in normally reading and dyslexic children.

Consistent with previous developmental ERP investigations (Martin, Shafer, Morr, Kreuzer, & Kurtzberg, 2003; Shafer, Morr, Kreuzer, & Kurtzberg, 2000, but see Ponton et al., 2000), MMN responses in children were delayed as compared to those of adults, with mean peak latencies at respectively 340 and 165 ms. A latency delay of ~175 ms in 8–11 year old children is larger than the delays typically reported for simple tone stimuli (Martin et al., 2003; Shafer et al., 2000). This increased delay probably relates to the complexity of our speech stimuli and is also consistent with previous findings indicating that CV-syllables elicit an MMN response at ~350 ms in 9.5-year-old children (Csépe, 1995).

The present study specifically investigated the influence of phonotactic probability on MMN activity elicited by HPP versus LPP non-words in normally reading and dyslexic children. In the following paragraphs we will discuss our MMN design and specific MMN findings in each of the subject groups. Both acoustic change detection and phoneme-specific processes contribute to the MMN response elicited by speech (Näätänen, 2001; Winkler et al., 1999). As we aimed to study neurophysiological correlates of a relatively high-level phonological process (as opposed to a mere acoustic process), we used a reversed MMN design, in which the contribution of acoustic processes is minimized (Bonte et al., 2005; Eulitz & Lahiri, 2004). First, MMN difference waves were derived from the ERP activity elicited by the same non-word presented as standard and deviant in separate experimental blocks. This provided a measure of MMN responses to HPP vs. LPP non-words independent of variation in ERP morphology that resulted from physical stimulus differences per se, i.e. generally enhanced ERP responses to *notsel* versus *notkel* (see Fig. 2). Second, we used four utterances of each non-word stimulus so that both standard and deviant stimuli were acoustically variable (see Fig. 1). Such acoustic variability is typical in natural speech and reduces the likelihood that the MMN is determined by only one or a few particular acoustic features (Eulitz & Lahiri, 2004; Jacobsen et al., 2004). Third, across experimental blocks, the acoustic difference between standard and deviant stimuli was identical, with the only difference being the directionality of change: standard → deviant was either *notsel* → *notkel* or *notkel* → *notsel*. It is unlikely that

the opposite MMN findings in normally reading and dyslexic children can be fully explained by an acoustic directionality effect. Furthermore, if directionality of consonant change would for example trigger the enhanced MMN for *notsel* in the context of *notkel* in normal readers, a smaller MMN enhancement would be expected for *notsel* in the context of an acoustically more similar LPP non-word like *notfel*. However, in our previous study with adults, the non-word *notsel* (HPP) elicited a very similar enhanced MMN response in the context of *notfel* (LPP) as in the context of *notkel* (LPP) (Bonte et al., 2005). Moreover, in that study, an MMN enhancement was not observed in a third acoustic control experiment with stimuli having comparable phonotactic probability (*so-fo*). Given the amount of nonlinearities in the auditory system and the acoustic complexity of natural speech stimuli, however, a partial contribution of ‘directionality’ to the observed effects cannot be excluded completely.

In normally reading children, *notsel* (HPP) elicited a strong MMN response around 340 ms after auditory stimulus deviation. In contrast, *notkel* (LPP) led to a significantly reduced MMN effect within the same latency range. Because adults demonstrated similarly enhanced MMN responses for HPP as compared to LPP non-words (Bonte et al., 2005), our MMN findings indicate comparable functional properties in 7–9 year old normally reading children and adults and suggest similar auditory cortical tuning to distributional frequencies of phoneme sequences in the speech input.

Crucially, MMN effects of dyslexic children did not indicate this sensitivity to phonotactic probability. Instead, these children showed an enhanced MMN response to the LPP non-word *notkel* and no clear MMN response to the HPP non-word *notsel*. Previously reported MMN results with dyslexic adults are variable and partly contradictory. Diminished MMN responses have been reported for speech but not tone stimuli (Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001), complex tone patterns (Kujala et al., 2000; Kujala, Belitz, Tervaniemi, & Näätänen, 2003) pitch changes but not duration changes of tones (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999) and pitch changes in the left but not the right auditory cortex (Renvall & Hari, 2003). Furthermore, dyslexic adolescents were found to have diminished MMN responses to speech but not to tone stimuli (Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998). Our findings indicated anomalous phonological change detection responses in dyslexic children for a phoneme contrast that may be assumed to be normally processed at an acoustic–phonetic level (similarly enhanced N2–N4 responses to *notsel* vs. *notkel* stimuli in dyslexic and normally reading children). These results confirm and extend previous ERP findings of a phonological priming study that indicated specific processing anomalies in dyslexic children during the prelexical phonetic–phonological processing of words, along with normal processing at a phonological–lexical level (Bonte & Blomert, 2004). In particular, the present results support the hypothesis that developmental dyslexia involves a subtle speech perception deficit that may not be reducible to a low-level auditory/sensory deficit (Blomert, Mitterer, & Paffen, 2004; Kronbichler, Hutzler, & Wimmer, 2002; Ramus et al., 2003).

What type of speech perception deficit may underlie the present findings in dyslexic children? Recent behavioural findings suggest that the quality of individual phoneme representations used during natural speech perception is similar in dyslexic and normally reading children (Blomert et al., 2004). Moreover, Serniclaes, Sprenger-Charolles, Carre, and Demonet (2001) reported that individuals with dyslexia show an enhanced sensitivity to acoustic differences between different exemplars of the same phoneme category. Accordingly, we would suggest that the anomalous MMN response to phonotactic probability together with normal ERP responses to acoustic–phonetic stimulus differences in dyslexic children reflects a subtle deficit in the early phonetic–phonological processing of natural speech. In particular, these subtle speech perception anomalies may influence implicit statistical learning or representation of the distributional frequencies of phoneme combinations in the language input. It is not unlikely that these impairments may influence the aptness and speed of processing involved in the mapping of phonological and orthographic strings of letters during early literacy acquisition.

5. Conclusion

We used a reversed oddball design to investigate implicit speech perception (in)capacities in dyslexic and normally reading children. Our findings suggest normal acoustic versus anomalous phonological speech processing in dyslexic children. Non-words elicited a pattern of ERP activity that indicated normal acoustic processing of the phoneme contrast used in the present study (/ts/ vs. /tk/). However, ERP mismatch results indicated a strikingly different influence of phonotactic probability on the processing of these phonemes. MMN responses of normal readers replicated previous results of adults (Bonte et al., 2005), and indicate auditory cortical tuning to statistical regularities of phoneme sequences. In contrast, MMN responses of dyslexic subjects did not show this neurophysiological sensitivity to variations in phonotactic probability. These findings provide additional insight in the often reported phonological problems in dyslexic children which may relate to subtle deficits during the implicit phonetic–phonological processing of natural speech.

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