

# Children with dyslexia reveal abnormal native language representations: Evidence from a study of mismatch negativity

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## Abstract

Although a deficit perceiving phonemes, as indexed by the mismatch negativity (MMN), is apparent in developmental dyslexia (DD), studies have not yet addressed whether this deficit might be a result of deficient native language speech representations. The present study examines how a native-vowel prototype and an atypical vowel are discriminated by 9-year-old children with ( $n = 14$ ) and without ( $n = 12$ ) DD. MMN was elicited in all conditions in both groups. The control group revealed enhanced MMN to the native-vowel prototype in comparison to the atypical vowel. Children with DD did not show enhanced MMN amplitude to the native-vowel prototype, suggesting impaired tuning to native language speech representations. Furthermore, higher MMN amplitudes to the native-vowel prototype correlated with more advanced reading ( $r = -.47$ ) and spelling skills ( $r = -.52$ ).

**Descriptors:** Language/speech, Children/infants, EEG/ERP, Dyslexia, MMN, Native speech sound representations

## Developmental Dyslexia

Developmental dyslexia (DD) is a specific developmental disorder that affects about 5%–10% of school-aged children (Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001; Lyon, Shaywitz, & Shaywitz, 2003; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Vellutino, Fletcher, Snowling, & Scanlon, 2004). It has a complex etiology and is clinically characterized by severe reading problems, often accompanied by a comorbid spelling

disorder, which interfere with academic achievement or activities of daily living that require reading skills (Shaywitz et al., 1999). These difficulties cannot be attributed to below-average general intelligence, gross neurological deficits, or uncorrected visual or auditory problems (Dilling, Mombour, & Schmidt, 2008; American Psychiatric Association, 2000). The underlying causes of DD are not well understood, although it is clear that DD is a disorder influenced by both neurobiological (Habib, 2000) and genetic factors (Paracchini, Scerri, & Monaco, 2007; Scerri & Schulte-Körne, 2010).

## Auditory Processing Deficits in Developmental Dyslexia

Efforts to pinpoint the underlying mechanisms of DD have resulted in a substantial body of evidence that points toward auditory processing deficits. These deficits are particularly prevalent in the analysis of phonemes but also in the acoustic analysis of general sounds, such as simple tones, and are believed to result from deviant neurophysiological responses to sounds within the primary and secondary auditory cortices.

The majority of studies investigating general auditory and speech perception in DD have examined the mismatch negativity (MMN), an event-related potential (ERP) component that provides a good measure of auditory perception and function and is typically observed between 100 and 250 ms (Näätänen, Gaillard, & Mantysalo, 1978; Näätänen, Paavilainen, Rinne,

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& Alho, 2007). MMN is generated by the automatic response of the brain to a mismatch in auditory stimulation. It is elicited when a deviant stimulus (e.g., with a probability of 15%) appears within a train of repeatedly presented standard stimuli (e.g., with a high probability of 85%). The MMN is observed irrespective of the subject's direction of attention (Näätänen et al., 1978) and is a good measure of the auditory system's ability to detect differences between sounds (Näätänen et al., 2007).

Tallal was the first to suggest that poor language skills in DD might arise from a general deficit in processing rapidly occurring temporal information (Tallal, 1975, 1980; Tallal & Piercy, 1973). She and her coworkers could show that individuals with DD performed worse when discriminating between rapidly presented stimuli, regardless of whether they contained speech relevant information or not. However, when the stimuli were presented at slower rates, perception improved. ERP research investigating general auditory processing has also found evidence for abnormal temporal integration of tones in DD indicated by absent or attenuated MMN to deviant tones occurring within the middle or at the end of a pattern (Kujala, Belitz, Tervaniemi, & Näätänen, 2003; Kujala et al., 2000; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999). Furthermore, significant evidence has been found for general acoustic processing deficits perceiving spectral features of simple tones. For example, pitch discrimination requires a person to successfully determine whether two tones differ in frequency (e.g., a tone of 50 Hz vs. a tone of 90 Hz). Generally, MMN investigations suggest that individuals with DD have difficulties discriminating tones that differ by less than 100 Hz (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Kujala et al., 2003; Maurer, Bucher, Brem, & Brandeis, 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001). Although the ability to discriminate between contrasting frequencies and tone patterns is relevant for speech perception and point toward a general auditory deficit in DD, other aspects of general auditory processing also relevant for speech perception such as tone duration have not revealed significant deficits in DD (Baldeweg et al., 1999; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007; Kujala, Lovio, Lepisto, Laasonen, & Näätänen, 2006; Schulte-Körne & Bruder, 2010, for review).

Furthermore, numerous investigations have revealed speech perception deficits in DD. Speech perception refers to the perception of phonemes in the earliest cortical stages of auditory analysis and involves the mapping of basic auditory information onto phonological units. Attenuated or late MMN in both children and adults with DD point toward deficits in discriminating between phonemes, regardless of whether the stimuli differed on spectral (e.g., formant transitions /da/–/ga/; Kraus et al., 1996; Maurer et al., 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998, 2001) or temporal levels (e.g., voice onset time transitions /ga/–/ka/; Bitz, Gust, Spitzer, & Kiefer, 2007; Cohen-Mimran, 2006; for reviews, see Bishop, 2007; Hämäläinen, Salminen, & Leppänen, 2011; Schulte-Körne & Bruder, 2010). In addition, longitudinal studies with infants who had a genetic risk for DD revealed abnormal ERPs to speech sounds at birth in comparison to infants without a genetic risk for DD (Leppänen, Pihko, Eklund, & Lyytinen, 1999; Molfese, 2000; Molfese, Molfese, & Modgline, 2001). Molfese (2000) was able to show that the deviant neurophysiological responses recorded at birth in at-risk infants reliably predicted DD and reading level at 8 years of age. Furthermore, MMN-like activity at birth in at-risk infants correlated with lower word and nonword reading accuracy in the first grade of school (Lyytinen et al., 2005); poorer language skills

at 2.5 years; poorer verbal memory at 5 years (Guttorm et al., 2005); and reduced phonological skills, slower lexical access, and less knowledge of letters at 6.5 years (Guttorm, Leppänen, Hämäläinen, Eklund, & Lyytinen, 2010). Altogether, these findings demonstrate the usefulness of the MMN component as a tool for studying speech perception in DD and strongly suggest that DD is characterized by difficulties in accurately perceiving phonemes that arise as early as the pre-attentive auditory level of analysis.

### Native Language Speech Perception

In healthy populations and for most sounds, MMN amplitude increases with an increase in the acoustic discrepancy between standard and deviant stimuli for most sounds (e.g., Näätänen et al., 2007; Sams, Paavilainen, Alho, & Näätänen, 1985; Tervaniemi, Schroger, Saher, & Näätänen, 2000; Yago, Corral, & Escera, 2001). However, for phoneme discrimination, MMN shows a more complex response pattern, reflecting activity related to the specific neural networks underlying speech that are dependent on a listener's native language (Näätänen et al., 1997; Rinker, Alku, Brosch, & Kiefer, 2010; Shafer, Schwartz, & Kurtzberg, 2004; Winkler et al., 1999). In these studies, stimuli representing native-language phonemes have repeatedly been shown to elicit an enhanced MMN response in comparison to nonnative phonemes (i.e., phonemes not belonging to any native phonemic category). These findings suggest that long-term memory representations of native phonemes automatically contribute to the processing of relevant speech features in the brain as early as 100 ms after stimulus onset.

Neural representations of phonemes belonging to a child's native language begin to be laid down within the first year of life. At birth, human infants are able to detect any phonemic difference independent of language (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Lasky, Syrdal-Lasky, & Klein, 1975; Streeter, 1976). However, between 6 months and 12 months of age the developing brain begins to respond preferentially to phonemes inherent to the infant's native language (Cheour et al., 1998; Gervain, Macagno, Cogoi, Pena, & Mehler, 2008; Gervain & Mehler, 2010; Kuhl, 2004; Kuhl, Tsao, Liu, Zhang, & De Boer, 2001; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005) and simultaneously begins to lose the ability to discriminate between non-native phonemes (Best & McRoberts, 2003; Rivera-Gaxiola, Silva-Pereyra, et al., 2005; Werker & Tees, 1984).

The extent of the loss of the ability to perceive nonnative phonemes is believed to be strongly coupled with the success in perceiving native language phonemes. Kuhl (2004) has termed this process the native language neural commitment (NLNC) hypothesis. She suggests that in the first year of life a child's brain begins to neurally commit to phonemes distinct to his or her native language. An increase of neural commitment (i.e., an enhanced ability to detect native language phonemes) is important for the development of advanced language skills, as the brain can more easily facilitate increasingly complex language units. In the same sense, children with strong NLNC also exhibit a stronger loss of the ability to discriminate between phonemes of irrelevant languages. Comparatively, children who retain good abilities to decipher phonemes of irrelevant languages exhibit less NLNC and consequently develop poorer language skills.

This developmental phenomenon was shown in a series of ERP and behavioral experiments (Kuhl et al., 2008; Kuhl, Conboy,

Padden, Nelson, & Pruitt, 2005; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005). These studies found that enhanced acoustic discrimination of native phonemes was related to the development of more sophisticated language skills, whereas enhanced acoustic discrimination of nonnative phonemes was correlated with less sophisticated language skills at later ages. For example, Rivera-Gaxiola, Klarman, et al. (2005) demonstrated that enhanced MMN-like responses to native phonemes at 11 months predicted greater vocabulary size at 18, 22, 25, 27, and 30 months; however if MMN-like responses were enhanced to nonnative phonemes, vocabulary size was found to be significantly reduced at all time points. Similarly, Kuhl et al. (2008) found that good phoneme discrimination skills at 7.5 months correlated with both better word production and sentence complexity at 24 months of age.

Investigations with infants suggest that the neural mechanisms underlying the processes involved in tuning for native language phonemes might follow statistical probabilities. Specifically, the distributional patterns of native-language phonemes are believed to provide clues about the phonemic structure of a language (e.g., distributional frequencies are low at category boundaries; Kuhl, 1993, 2004; Kuhl et al., 1992; Maye, Werker, & Gerken, 2002). In support of this assumption, Gervain et al. (2008) found that newborns possessed the ability to detect and learn distributional patterns and that this ability was associated with activity in temporal and left frontal areas. Furthermore, these cortical areas were also found to be involved in learning and memory of phonemic patterns in infants (Dehaene-Lambertz & Baillet, 1998; Dehaene-Lambertz & Gliga, 2004; Dehaene-Lambertz, Hertz-Pannier, Dubois, & Dehaene, 2008; Dehaene-Lambertz et al., 2006).

Together, these findings highlight the importance of the ability of the developing brain to tune to native language cues. The research to date highlights a dynamic developmental process where foundations for native language speech representations are laid down at an early age and are related to normal language acquisition and to success in later language skills.

### Dyslexia and Native Language Speech Representations

Although a large body of evidence from MMN studies suggests that DD is characterized by a deficit in discriminating between phonemes, the question of whether this deficit is general to all speech sounds or specific to sounds of one's native language has not been systematically examined. In a recent study, Bonte, Poelmans, and Blomert (2007) employed pseudowords to examine phonological processing in DD. One pseudoword contained a phoneme with a high probability for the Dutch language whereas the other pseudoword contained a phoneme with a low probability for the Dutch language. Thus, both pseudowords were relevant for the children's native language, differing only in terms of their probability of occurrence. Replicating an earlier study with adults (Bonte, Mitterer, Zellagui, Poelmans, & Blomert, 2005), the authors found that children without any reading difficulties exhibited an enhanced MMN to the highly probable pseudoword in comparison to the equally complex but less statistically probable pseudoword. Although the child participants with DD were able to detect the differences in the stimuli, as evident by the presence of MMN in both conditions, they did not exhibit enhanced MMN to the highly probable stimulus. This finding suggests that brain processes recorded from children with DD in response to frequently heard native language phonemes do not reflect exposure to their native language over time, im-

plying inefficient native language representations. Furthermore, the data suggest that the deficit might lie in a lack of coding for statistical regularities in language, which as reviewed, is an important foundation for acquiring good language skills and which begins to shape the formation of speech representations within the first year of life.

### Study Goal

The present study's aims were to further examine native language phonetic perception skills in children with DD and extend previous findings (Bonte et al., 2007) using MMN. We employed two types of within-category phonemic stimuli: (1) a phoneme representing a native language prototype ("native-vowel prototype") and (2) an atypical phoneme belonging to the same phonemic category but nonprototypical ("atypical vowel"). Importantly, the present study differed from the study by Bonte et al. (2007) on two levels: stimulus complexity and stimulus relevance for the native language. Bonte et al. (2007) used pseudowords with either a high or a low degree of probability in the Dutch language. The stimuli employed in the present study are, in contrast, phonemes and do not reflect the degree of probability of occurrence in the German language, but rather represent prototypicality of stimulus representation for German speakers. Thus, atypical stimuli represent "awkward" exemplars of German phonemes and are not identified as good exemplars by native speakers (see Methods). As a control condition, complex tone stimuli matched to the vowel sounds for acoustic complexity were presented to the children.

As native speech representations are being shaped from birth and because adults show enhanced MMN to native speech sounds, we hypothesized that children with no history of reading or language difficulties would also show enhanced MMN to their native-vowel prototype in comparison to the MMN of the atypical vowel. Although the acoustic differences in the speech stimuli were greater between the standard stimulus and the atypical vowel (as compared to the native-vowel prototype) a greater MMN to the native speech sound was expected because of the anticipated recruitment of additional neural resources for the native-vowel prototype. Based on previous findings suggesting inefficient native language sound processing and a deficit processing phoneme differences in general, we hypothesized that the DD group would not exhibit enhanced MMN amplitude in response to a prototypical stimulus. Finally, in our complex-tone control condition we did not expect to find group differences in MMN as stimuli differences exceeded 100 Hz.

## Methods

### Subjects

Children ranging from 8 years, 6 months to 9 years, 8 months were contacted from a pool of families that had expressed interest in participating in studies within our institute. In total, 30 monolingual German children were recruited for the study. Fifteen of these children were assigned to the control group and 15 children were recruited for the clinical comparison group.

During the recruitment procedure, potential participants were excluded if one of the parents indicated that his or her child had a multilingual background, had a history of specific language disorder, had experienced a serious head trauma, or had a history of

**Table 1.** Descriptive Statistics of Control Children (CC) and Children with Developmental Dyslexia (DD)

	CC <sup>a</sup> M (SD)	DD <sup>b</sup> M (SD)	Comparison
Age in months	110.67 (4.42)	110.43 (4.88)	$t(24) = 0.13, p = .898$
IQ	114.50 (12.71)	114.85 (14.87)	$t(24) = -0.065, p = .949$
Reading fluency <sup>c</sup>	51.50 (6.67)	28.50 (2.82)	$t(14.35) = 11.13, p < .0001$
Spelling <sup>c</sup>	55.58 (5.58)	41.00 (4.11)	$t(24) = 7.65, p < .0001$

Notes: Mean scores and standard deviations are presented for group averages.

<sup>a</sup>CC:  $n = 12$ ; 4 males.

<sup>b</sup>DD:  $n = 14$ ; 9 males.

<sup>c</sup>Values reported are standardized T values:  $M = 50$ ;  $SD = 10$ .

attention deficit and hyperactivity disorder (ADHD). Children were further excluded if they scored above average in the parent questionnaire of the Child Behavior Checklist 4-18 (CBCL; Achenbach, 1991) indicating a risk of ADHD. An estimation of IQ was obtained using a verbal and nonverbal subtest (Similarities and Block Design) of the German version of the Wechsler Intelligence Scale for Children (*WISC-IV*; Wechsler, 2003; German *HAWIK-IV*; Petermann & Petermann, 2007). Children who scored below average ( $< 85$  IQ points) were excluded.<sup>1</sup> Children's language skills and the diagnosis of DD were determined using measures of reading fluency (*One-Minute Fluent Reading Test* [German: *Eine Minute Leseflüssigkeitstest*]; Moll & Landerl, 2010) and an untimed spelling test (*Diagnostic Spelling Test for the 4th Grade* [German: *Diagnostischer Rechtschreibtest für die 4. Klasse*]; Grund, Haug, & Naumann, 2003). To ensure inclusion of only truly average (or above average) readers and spellers in our control sample, children belonging to the control group were required to be within 0.85 standard deviations of the lower end of the norm scale calculated in T values (mean 50;  $SD = 10$ ; cutoff criteria was therefore set to a T value of 41.5) for both measures. To be included in the group with DD, children were required to fulfill the diagnostic criteria for DD and thus had below average grade-based reading skills. Furthermore, the discrepancy between IQ and reading fluency was  $> 2 SD$  for all of the children with DD. Spelling ability was considered irrelevant for inclusion in the group with DD, as the diagnosis for DD is dependent on reading. Therefore, seven children with DD had average spelling skills and eight had below average spelling skills. Of the 30 children recruited, a total of three control children and one child from the DD sample were excluded from the analysis due to excessive EEG artifacts (two control children and one child with DD) or technical errors (one control child) while recording the EEG. All data reported exclude these participants. Table 1 describes and compares the control and experimental groups in terms of age, IQ, reading fluency, and spelling measures. Finally, sufficient auditory function in both ears was required and assessed with an audiometer. Children were required to hear a minimum of 20 dB on both ears for all of the following frequencies: 250, 500, 1000, 2000, 4000 Hz.

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Philipps University of Marburg. All participants and their par-

ents provided written informed consent, which was obtained prior to inclusion in the study.

### Stimuli and Procedure

In the speech condition, the stimulus set consisted of three within-category synthetic /y/ vowels and three complex non-speech stimuli. Praat software (Boersma & Weenink, 2006) was used for the creation of a set of 135 synthetic vowels covering the formant space for /y/ and the surrounding front high and front mid-high vowels of German, French, Finnish, and Hungarian (120 designated as /y/ and 15 catch trials designated as /i/, /e/, and /oe/). First, the glottal source was created by converting the pitch and timing information to a glottal source signal (0.1% noise was added to make the signal sound more natural). The duration of the source signal was 150 ms and the pitch fell linearly from 230 Hz at the onset to 200 Hz at the offset (mean pitch 215 Hz). The source was then filtered with a vocal tract model containing information about the frequencies and bandwidths of the 10 lowest formants (i.e., vocal tract resonances). All sounds were windowed by a 10-ms linear onset and a 15-ms offset ramp using CoolEdit 96 (Syntrillium Software [http://www.oldapps.com/CoolEdit.php?old\\_cooledit=10](http://www.oldapps.com/CoolEdit.php?old_cooledit=10)). Female pitch characteristics were used for all stimuli. In a second step, native speakers for each of the four languages (Finland: 23, France: 23, Germany: 20, and Hungary: 30) evaluated phoneme boundaries of all 135 vowel stimuli. The stimuli were tested for identity (/i/ or /y/ and catch trials /e/ or /oe/) and evaluated for goodness of identified vowels. Those identified as /y/ (with at least with 90% accuracy) and receiving the highest goodness rating by the same native speakers for each of the four listener groups were selected for use in future discrimination and ERP experiments. The results showed that Finnish and Hungarian listeners preferred the same vowel, and therefore this /y/-stimulus was used for both groups (referred to as Finnish-Hungarian).

For the nonspeech condition, complex tone equivalents for speech stimuli were created by synthesizing five separate sine wave tones at the frequencies corresponding to the first five formant peaks used in the vowel synthesis parameters. The amplitudes of the sine tones were matched according to values obtained by directly measuring the formant amplitudes of the selected synthesized vowels with Praat. The complex tone stimuli were composed of five sine tones located at frequencies corresponding to the lowest five formants of the synthetic vowels, thus rendering them analogous to the vowel stimuli but lacking speech structure. The formant frequencies of the first five formants (identical for vowels and complex tones) for all stimuli are presented in Table 2 and the

<sup>1</sup>An estimation of IQ can be obtained by adding the standardized scores of both tests and then multiplying by 5: (Similarities Standardized Score + Block Design Standardized Score) \* 5). The value obtained can then be used in the IQ tables provided. A standard score of 8 on both tests is the minimum possible for inclusion.

**Table 2.** First Five Formant Frequencies (Hz) for the Deviant Stimuli and the Standard Stimuli Used in the Experiment, Native-/y/ and Atypical-/y/, and Their Corresponding Complex Tones

		Formant 1	Formant 2	Formant 3	Formant 4	Formant 5
Deviant stimuli						
German	Native-vowel and matching complex tone	250	2018	2400	3500	4500
French	Atypical-vowel and matching complex tone	250	2086	2400	3500	4500
Standard stimulus						
Finnish–Hungarian	Atypical-vowel and matching complex tone	274	1886	2400	3500	4500

stimuli are depicted in Figure 1. For vowels, five additional formants were used (F6–F10: 5500, 6500, 7500, 8500, and 9500 Hz).

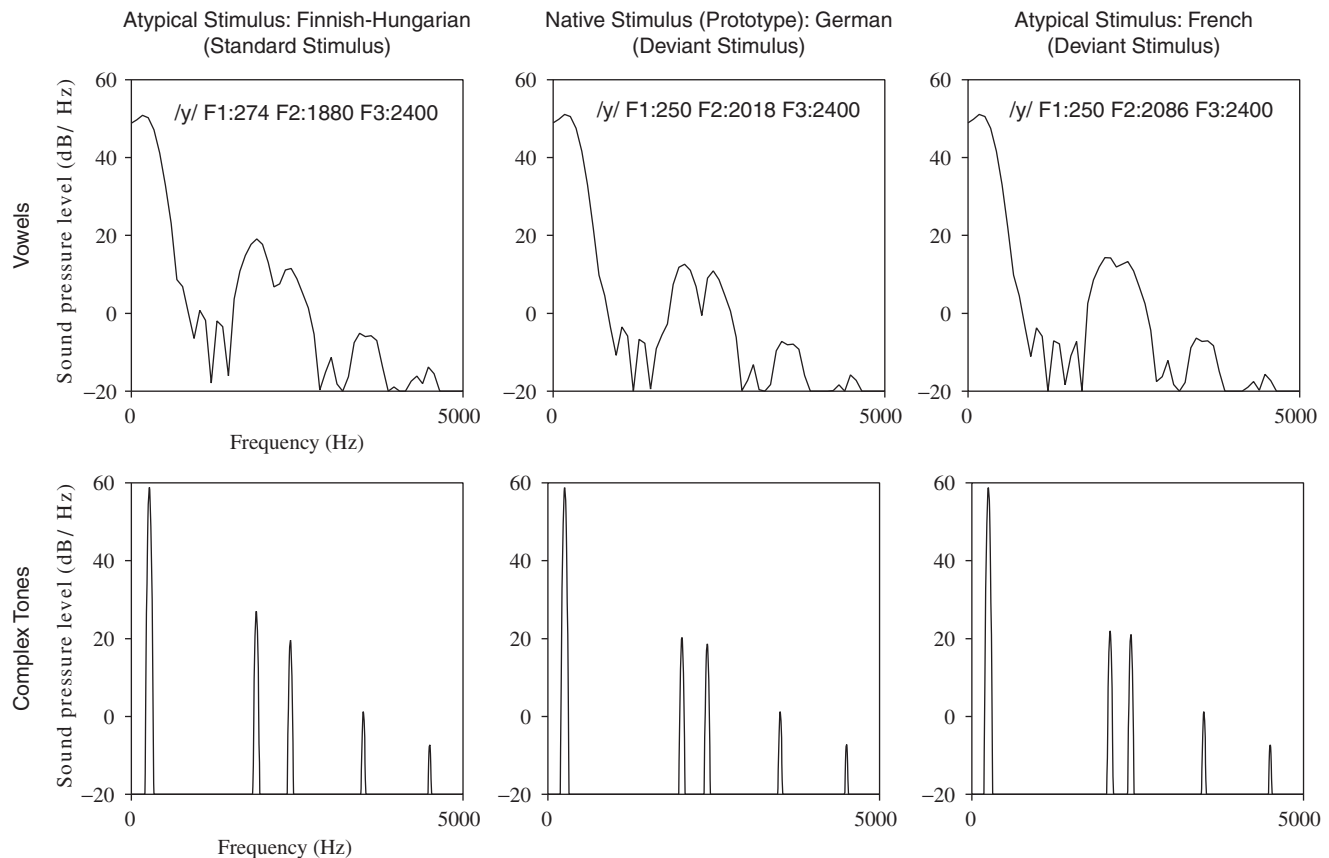
For the present experiment, the Finnish–Hungarian vowels and complex tones were used as the standard stimuli in the speech and complex tone conditions, respectively. Within these conditions and in separate blocks, German and French vowels and complex tones were the deviant stimuli.

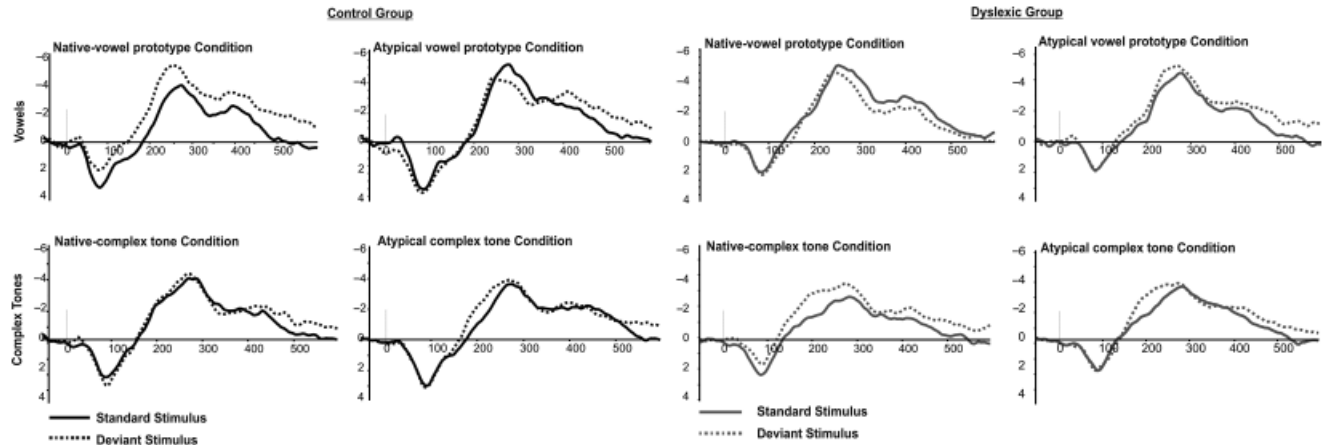
The French and German within-category /y/ and complex tone stimuli differed only at F2 by 68 Hz and were therefore very similar. In comparison to the German stimuli, the French vowel and complex tone stimuli were acoustically more distinct from the Finnish–Hungarian vowel and complex tone standard stimuli at F2 with a difference of 200 Hz, compared to a difference of 132 Hz at F2 for German. Both French and German stimuli differed from the Finnish–Hungarian stimuli at F1 by 24 Hz. Although individuals with DD have a general acoustic deficit discriminating between different frequencies, this has largely only been reported when frequency differences were less than 100 Hz (see Hämäläinen et al., 2011; Schulte-Körne & Bruder, 2010, for re-

view); therefore we expected to see MMN in all conditions for the group with DD.

The stimuli were presented in a typical oddball paradigm in separate blocks pseudorandomly for the two conditions (first two complex tone blocks, followed by two speech blocks) using E-Prime software (<http://www.pstnet.com/eprime.cfm>). In the two speech sound blocks, the Finnish–Hungarian /y/ was the standard stimulus. In one block, the French /y/ served as the deviant stimulus and in the other block the German /y/ was the deviant speech sound stimulus. The presentation of these blocks was counterbalanced across participants. In this article we refer to the deviant vowel stimuli as “atypical vowel” (i.e., French vowel) and “native-vowel prototype” (i.e., German vowel), respectively. Two complex tone conditions were analogous: French = “atypical-complex tone”; German = “native-complex tone.” These conditions were also presented in separate blocks counterbalanced across participants.

The standard stimuli occurred with a probability of  $p = .82$  ( $n = 576$ ), and deviant stimuli occurred with a probability of

**Figure 1.** The short-term spectrum of the vowel stimuli (upper row) and the short term spectrum of the complex tone stimuli (bottom row) for the standard stimuli (first column) and the deviant stimuli (second and third columns).



**Figure 2.** Standard and deviant ERP responses at electrode 11 (approximately Fz) to both vowels (top panel) and to both complex tones (lower panel) in the control group (left; black) and the group of children with DD (right; gray). Responses to standard stimuli are depicted with a solid line and the responses to the deviant stimuli are illustrated with a dotted line.

$p = .18$  ( $n = 126$ ). Stimuli were presented with a pseudorandom stimulus onset asynchrony (SOA) of 600–700 ms (mean: 650 ms) and with an intensity of approximately 70 dBA. At least three standard stimuli occurred before and after each deviant stimulus. Stimuli were administered binaurally using PX200 Sennheiser headphones, and attention was diverted with an engaging silent film. Total recording time was approximately 40 min.

After ERP recording children performed a short same–different task. The children made rapid judgments between the vowels and complex tones (i.e., whether or not two sounds were the same or different) used in the ERP experiment using right and left arrow keys (correct answers counterbalanced across trials). Vowels and complex tones were presented in separate conditions and balanced across participants. Sounds were presented in pairs of two with 310 ms between sound presentations. The beginning of each trial was initiated by the child by pressing a key. Children were given a maximum of 4 s to answer. In a training session, children became familiar with the experimental paradigm and were provided with feedback (happy or sad faces). Feedback was not provided in the actual test session. The task consisted of 10 “same” (e.g., French-vowel vs. French-vowel) and 10 “different” (e.g., French-vowel vs. German-vowel) pairs for each possible stimulus comparison (Finnish–Hungarian, French, German)  $\times$  category (vowels, complex tones), resulting in 120 total trials. For reaction times, only correct answers were analyzed, and extreme values ( $\pm 1.5$   $SD$  from the mean) were eliminated ( $< 1\%$  of data).

### EEG Recording and Averaging

EEG was recorded continuously with an Electrical Geodesic Inc. 128-channel system with Cz as the reference electrode (Figure 2, electrode 129). The impedance was brought to below 50 k $\Omega$  before recording and monitored and corrected at regular intervals. The quality of EEG data was monitored throughout the recording session and sampled at 250 Hz. Further analyses steps were performed with Brainvision Analyzer. After removing all EOG artifacts with Independent Component Analysis, exclusion of other artifacts (gradient: max 50  $\mu$ V; max–min: 150  $\mu$ V for 200-ms windows; amplitude: min  $< -150$   $\mu$ V; max  $> 150$   $\mu$ V; low activity: 0.50  $\mu$ V for 100-ms windows), and filtering (bandpass 0.3–30 Hz), the EEG was referenced to the average reference. ERPs were calculated by averaging epochs of 650 ms (including a

prestimulus baseline of 50 ms) separately for the standard and deviant stimuli for each participant and condition. Only the responses to the standard stimuli presented before the deviant stimuli were included in the current analyses, resulting in 126 possible EEG epochs for each of the two stimulus types. A minimum of 50 usable trials was necessary for inclusion in the statistical analysis. The averages for the accepted trials were (mean ( $SD$ )) control group: native-vowel prototype 100 (15); atypical vowel 100 (18); native-complex tone 110 (11); and atypical-complex tone 109 (15); and DD group: native-vowel prototype 104 (12); atypical vowel 107 (10); native-complex tone 108 (9); and atypical-complex tone 113 (11).

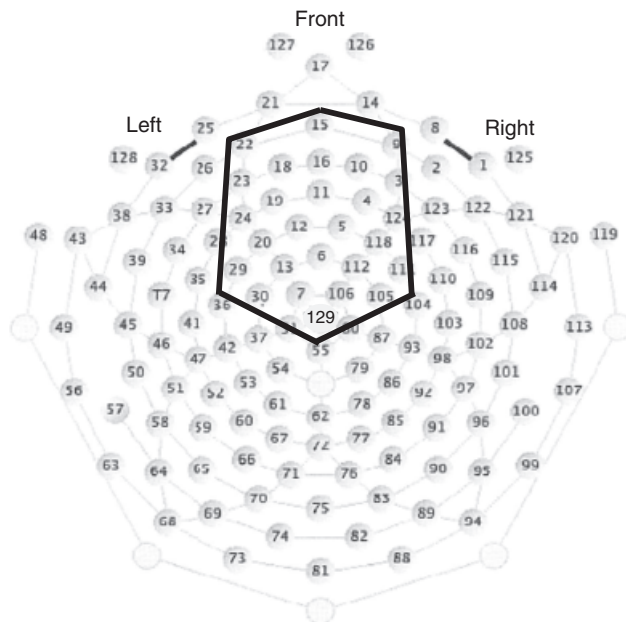
### Data Measurement and Analysis

Standard and deviant stimuli elicited distinct ERPs both in the control group and the group with DD (Figure 2). MMN was estimated statistically by subtracting the ERPs to the standard stimulus from those to the deviant stimulus at fronto-central electrodes for both speech and complex tone stimuli. Visibly, the most distinct MMN occurred to the native-vowel prototype for control children. Based on this, a window of a significant MMN response displaying negative amplitude was determined using running  $t$  tests of MMN amplitude against zero on the grand average waveforms at each electrode. This analysis resulted in a time and spatial region of interest over 27 fronto-central electrodes (Figure 3) with significant activity at 116–260 ms, which was applied to all conditions and was also used for group comparisons. As distinct peaks were not evident for all MMN windows, mean amplitudes were calculated for each condition separately.

Repeated measures analyses of variance (ANOVAs) were performed on the behavioral and MMN data. For the behavioral data, separate ANOVAs were run over accuracy and reaction time with the within subject factors speechness (vowels, complex tones)  $\times$  condition (same, different) and the between subject factor group (control, dyslexic). Only reaction times for correct answers were analyzed.

With regard to the MMN data, we first examined MMN responses using ANOVAs comparing the two groups using the between-subjects factor group (control, dyslexic) and the within-subject factors typicality (native, atypical) and electrode (all 27 electrodes). We conducted another set of ANOVAs where we





**Figure 3.** Illustration of the 128-channel system and electrode position taken from *Geodesic Sensor Net Technical Manual* (Electrical Geodesics, Inc., 2007). The selected area depicts the electrodes chosen for this study. Electrode 11 is approximately Fz; 129 is approximately Cz.

excluded midline electrodes (15, 16, 11, 6, 129; see Figure 3) in order to determine whether any MMN differences between the two hemispheres existed using the within-subject factors typicality (native, atypical), hemisphere (left, right), and electrode. These were followed by individual analyses using the same set of ANOVAs at the group level in order to describe the response to these stimuli in healthy children and those with DD separately. Overall, ANOVAs for the MMN analyses were conducted separately for vowels and complex tones. In the case of significant interactions, post hoc ANOVAs were used to determine the source of significance. The alpha level for all analyses was .05. Greenhouse–Geisser and Bonferroni corrections were applied when appropriate.

## Results

### Behavioral: Same–Different Task

**Accuracy.** ANOVAs performed on the accuracy data revealed that children with DD and control children did not differ in their ability to actively discriminate between the vowels or complex tones in the same–different task. Overall, a main effect for speechness was found,  $F(1,24) = 80.63$ ,  $p < .0001$ ,  $\eta^2 = 0.12$ , revealing significant differences discriminating between vowels and complex tones. Discriminating between vowels was more difficult than discriminating between tones (mean [SD]: vowels 59.15% [3.66], complex tones 73.81% [2.13]). An overall main effect of condition,  $F(1,24) = 35.10$ ,  $p < .0001$ ,  $\eta^2 = 0.11$ , reflects a higher accuracy for same decisions (75.72% [3.22]) compared to different decisions (56.24% [3.40]). As can be seen in Figure 4, for both vowel and complex tone conditions, French versus German response accuracy was below 50% for both control children and children with DD, suggesting that these sounds were very difficult to discriminate. Two post hoc ANOVAs were run to further examine these performance measures within the different judgments with the factor comparison type (Finnish–Hungarian vs. French, Finnish–Hungarian vs. German, and French vs. Ger-

man). For both vowels,  $F(2,48) = 35.52$ ,  $p < .0001$ ,  $\eta^2 = 0.56$ , and complex tones,  $F(2,48) = 126.89$ ,  $p < .0001$ ,  $\eta^2 = 0.83$ , pairwise comparisons showed that Finnish–Hungarian versus French comparisons were more accurate than Finnish–Hungarian versus German comparisons, which were more accurate than French versus German comparisons.

**Reaction times.** No differences between groups, no interactions, and no main effects were found for reaction time measures (see Figure 5).

### MMN

#### Group comparisons.

**Vowels.** A Typicality  $\times$  Group interaction was observed for vowels,  $F(1,24) = 6.30$ ,  $p < .02$ ,  $\eta^2 = .19$ . Post hoc repeated measures ANOVAs revealed that children with DD had significantly attenuated MMN amplitudes to the native-vowel prototype when compared to the control group,  $F(1,24) = 2.57$ ,  $p < .000$ ,  $\eta^2 = .33$ . However, they had comparable MMN for the atypical vowel,  $F(1,24) = 0.71$ , n.s. (see Figure 6a,b). Our analysis of hemisphere revealed no main effects or interactions.

**Complex tones.** No group differences were found for complex tones (Figure 6a,b) and no differences between the left and right hemispheres were observed.

#### Control group.

**Vowels.** Figure 7a depicts MMN peak amplitudes calculated for the control children. MMN amplitude was significantly higher to the native-vowel prototype than to the atypical vowel,  $F(1,11) = 9.98$ ,  $p < .01$ ,  $\eta^2 = .48$ . MMN between the left and right hemispheres was similar for both vowel types.

**Complex tones.** For the control children, MMN did not differ for the native- and atypical-complex tones, neither for the overall analysis nor for the hemisphere analysis.

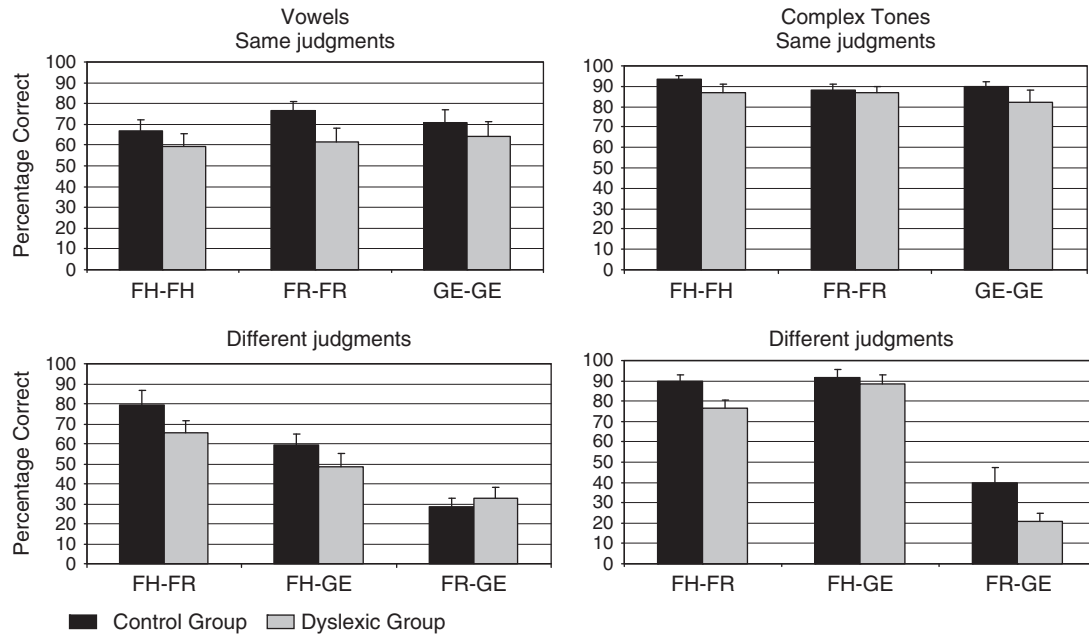
#### Developmental dyslexia group.

**Vowels.** The identical within-group analyses with the group of children with DD revealed no significant differences between the native-vowel prototype and the atypical vowel (Figure 7b). Thus, in contrast to the control group, children with DD did not reveal enhanced MMN to their native-vowel prototype.

**Complex tones.** Children with DD also revealed no MMN differences between the native- and atypical-complex tones (Figure 7b).

### Correlation Analyses

Based on the results of the group comparisons, post hoc Pearson correlations ( $r$ ; two-tailed) were conducted between MMN mean amplitudes (both the native-vowel prototype and atypical vowel) and language skills (reading and spelling measures) across both groups. For this analysis, an average of the MMN mean amplitude was taken over the 27 electrodes used in the analysis in order to avoid increasing the probability of a type I error caused by multiple testing. Significant correlations revealed that an increase in MMN amplitude in response to the native-vowel prototype correlated negatively with both the total number of words read per minute ( $r = -.47$ ,  $p < .02$ ) and overall spelling skills ( $r = -.52$ ,  $p < .01$ ). The negative correlations indicate that en-



**Figure 4.** Accuracy measures (percent correct) for same and different judgments. FH = Finnish–Hungarian vowel/complex tone; FR = French vowel/complex tone; GE = German vowel/complex tone. Bars depict the standard error of the mean.

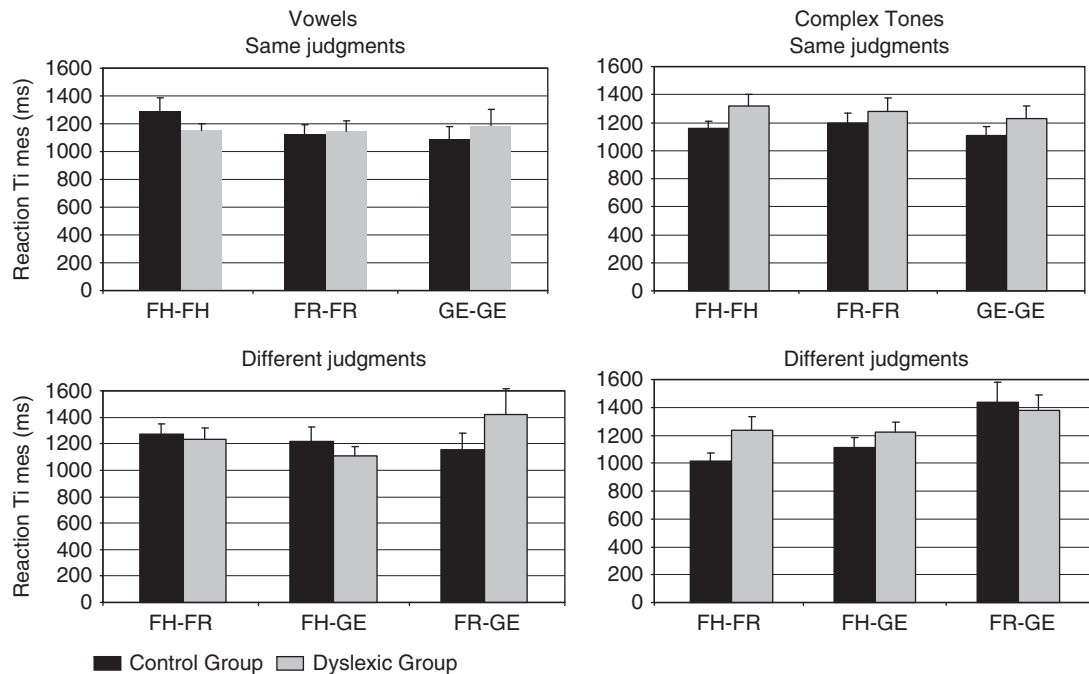
hanced MMN to the native-vowel prototype was associated with faster or more fluent reading and better spelling skills. There were no correlations with the atypical vowel. Table 3 depicts the correlation matrix.

### Discussion

The present study was designed to investigate native-language representations in German children with and without DD. Chil-

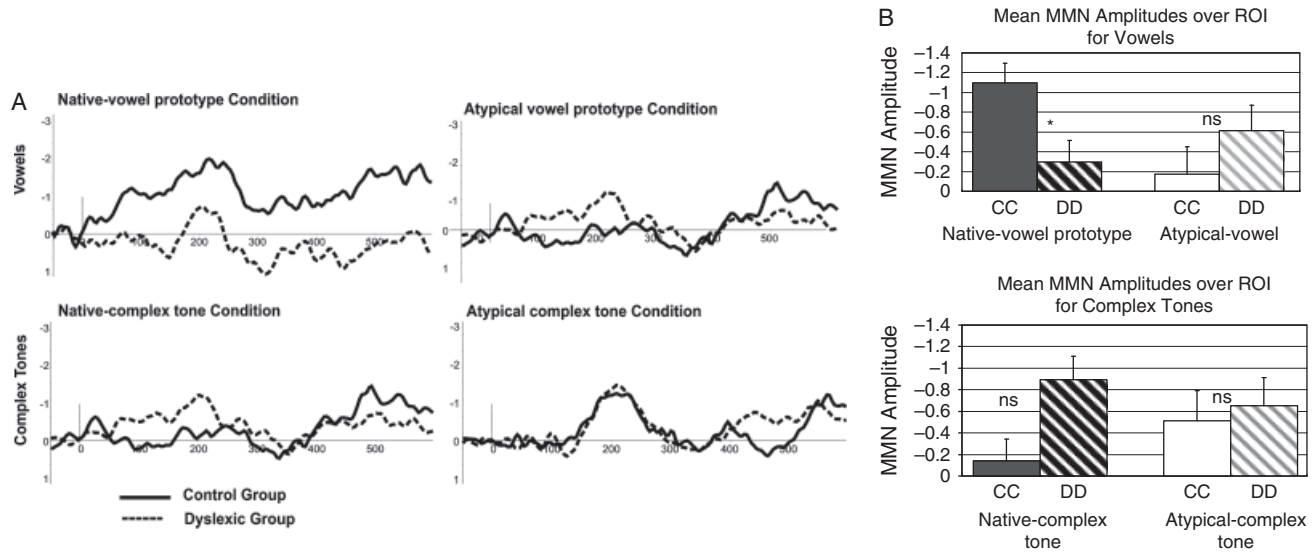
dren performed both passive and active discrimination tasks involving phonemes prototypical and atypical to their native language.

Neither accuracy nor reaction time measures in the same–different task revealed differences between how children with and without DD actively perceived the vowels and complex tones used in the ERP experiment. The native-vowel prototype (German) and atypical vowel (French) stimuli, which were used as deviants in the ERP experiment, were acoustically very similar, differing only at F2 by 68 Hz. The difficulty of this comparison at



**Figure 5.** Reaction time measures (in milliseconds) for same and different judgments (correct answers only). FH = Finnish–Hungarian vowel/complex tone; FR = French vowel/complex tone; GE = German vowel/complex tone. Bars depict the standard error of the mean.





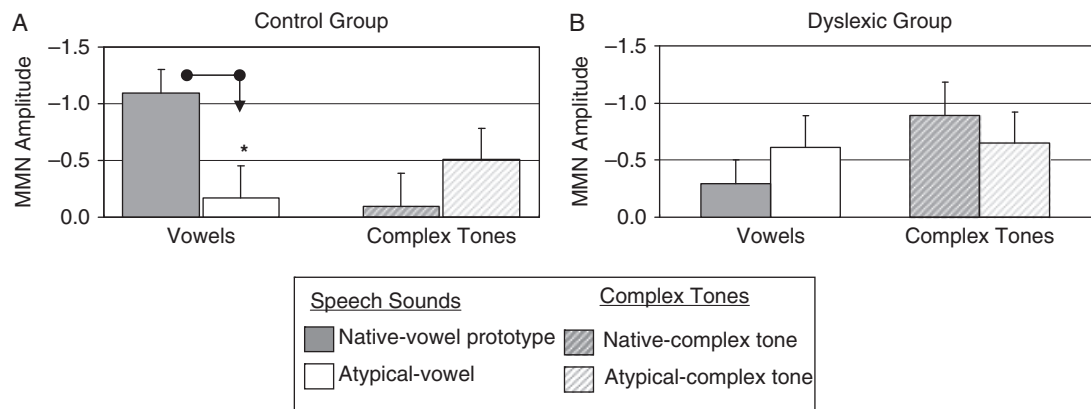
**Figure 6.** (A) Grand-average MMN difference waves (standard minus deviant) at electrode 11 (approximately Fz) for both the native-vowel prototype and the atypical vowel (upper panel) and for the native-complex tone and the atypical-complex tone (lower panel) conditions for both groups. Difference waves for the control children are depicted with solid lines and difference waves for the children with DD are depicted in dashed lines. (B) Average MMN amplitudes over all electrodes for the MMN speech sound conditions for control children and children with DD. In the native-vowel prototype condition, the difference between MMN mean peak amplitudes between the control children and children with DD is significant ( $*p < .05$ ); ns = not significant. Bars depict standard error of the mean. CC = control group. DD = dyslexic group.

the behavioral level was reflected by both control children and children with DD who had similarly low accuracy scores. Overall, the acoustic difference between the atypical vowel and the standard stimulus (Finnish–Hungarian) was greater than the acoustic difference between the native-vowel prototype and the standard stimulus. These differences were reflected in the accuracy measures, where both groups of children revealed better discrimination abilities between Finnish–Hungarian and French stimuli, than between Finnish–Hungarian and German stimuli.

Although no group differences were found during active discrimination, the analyses of the ERP measures revealed a unique pattern of results. In both groups, MMN was present in all conditions, indicating an intact change detection system. As hypothesized, control children showed a significantly enhanced MMN to the native-vowel prototype compared to the atypical vowel whereas children with DD did not show an enhanced MMN response to the native language stimulus. Furthermore,

group comparisons revealed that control children elicited a significantly greater MMN to the native-vowel prototype in comparison to children with DD. However, no MMN differences between the control children and the children with DD were found for the atypical vowel. These findings seem to suggest that the children in the control group were sensitive to prototypicality whereas the children with DD were not. As expected, the complex-tone control condition did not reveal any group differences.

Thus, the main difference between control children and children with DD in the present study was that children with DD did not show enhanced MMN to the native language vowel whereas control children did. These findings suggest that native-vowel prototypes recruit additional neural resources in early change detection in normally developing children and thus extend previous findings from adult populations (Näätänen et al., 1997; Rinker et al., 2010; Shafer et al., 2004; Winkler et al., 1999). However, despite exposure to a particular language over a long period of time, phonemes characterizing the native language of



**Figure 7.** Average MMN amplitudes taken over all electrodes for the corresponding MMN curves for control children (A) and for children with DD (B) ( $*p < .05$ ). Bars depict the standard error of the mean.

**Table 3.** Pearson (*r*) Correlations (Two-Tailed) between MMN Amplitudes to Both Vowel Stimuli and Spelling and Reading Measures

	MMN native vowel	MMN atypical vowel	Spelling	Reading fluency
MMN native vowel	1			
MMN atypical vowel	.009	1		
Spelling	-.522**	.232	1	
Reading fluency	-.471*	.168	.844**	1

Notes: Correlations conducted over all subjects ( $N = 26$ ).

\* $p < .05$ ; \*\* $p < .01$ .

an individual with DD do not seem to be reliably represented during acoustical analysis. What is more, the MMN response to the native-vowel prototype was related to reading and spelling skills, where increased neural recruitment was linked to more fluent and faster literacy skills. This finding is in line with studies in younger children that have demonstrated how native language representations are related to the development of literacy skills (Kuhl et al., 2005, 2008; Rivera-Gaxiola, Klarman, et al., 2005). Finally, although behavioral measures did not show a deficit in processing speech stimuli in the group with DD, the MMN measures did. These findings might possibly demonstrate top-down strategies for enhancing performance and suggest that MMN is a more sensitive indicator of perceptual deficits in DD.

In a similar study, Bonte et al. (2007) examined MMN to phonemes embedded within pseudowords that had either a high or a low statistical probability of occurrence within the Dutch language. Thus, the pseudowords contained phonemes that were both prototypical and native for the Dutch language. Pseudowords containing more statistically probable phonemes elicited an enhanced MMN in comparison to less statistically probable phonemes in healthy children; however, children with DD showed no MMN enhancement related to statistical probability but a MMN comparable to the stimulus with a low probability. Together, these results and our present findings suggest that DD might be characterized by a specific deficit in tuning to phonemic characteristics relevant for the individual's native language.

The present findings further extend results of previous investigations that revealed that DD is characterized by deficits in perceiving speech stimuli (consonant–vowel syllables) in general (for review, see Schulte-Körne & Bruder, 2010). Interestingly, our present findings suggest that children with DD can discriminate between vowels, as shown by both the behavioral findings and by a MMN response to the atypical vowel similar to that of the control children. However, when speech processing was examined in relation to a native vowel, the children with DD did not show an enhanced MMN. Enhanced MMN to native speech representations has already been reported in healthy populations (Näätänen et al., 1997; Rinker et al., 2010; Shafer et al., 2004; Winkler et al., 1999). The enhanced MMN likely reflects an important native language phoneme network involving neural resources from left frontal and temporal areas that represent the learned responses to prototypical phonemic representations (Dehaene-Lambertz & Baillet, 1998; Dehaene-Lambertz & Gliga, 2004; Dehaene-Lambertz et al., 2006, 2008; Gervain et al., 2008). Thus, the present findings seem to suggest that children with DD do not recruit extra neural resources when listening to native phonemes, which further suggests that these

phonemes might have a fuzzy or weaker representation in long-term memory.

One major difference between past studies and the present study on speech perception in DD lies within the choice of phonemes employed for acoustic comparison. All previous studies on phoneme perception in DD employed consonant–vowel (CV) stimuli (i.e., /ba/ vs. /da/) whereas the present study used vowel stimuli. In previous studies, CV stimuli differed in either their spectral or temporal properties. Spectral property changes refer to differences within formant transitions (i.e., /da/ vs. /ba/) whereas temporal property changes represent differences in phonemes based on voice transition onset time (i.e., /ba/ vs. /pa/). The vowels employed in the present study did not differ on either of these levels and, furthermore, belonged to the same phoneme category. In fact, they only differed slightly at F2 (where the atypical vowel was actually acoustically more distinct than the native vowel). Thus, the difference between MMN to the vowels in the present study can not be attributed to the perceptual level of analysis but can only be attributed to the prototypicality of the phoneme /y/. Therefore, a general speech processing deficit might be attributed to CV stimuli, where acoustic differences in formant frequency or in temporal aspects between stimuli determine the success of discrimination, in a similar manner as found in studies investigating nonspeech stimuli. However, for vowels, nativeness or prototypicality of the stimulus might play a more important role in speech perception.

As reviewed, the neural representations for the preferential encoding and perception of prototypes begin to be formed within the first year of life (Cheour et al., 1998; Gervain et al., 2008; Gervain & Mehler, 2010; Kuhl, 2004; Kuhl et al., 2001; Rivera-Gaxiola, Klarman, et al., 2005; Rivera-Gaxiola, Silva-Pereyra, et al., 2005). The findings from these studies further demonstrate that the extent to which infants neurally commit to the speech representations of their native language is reflected not only by how well they perceive phonemes belonging to their native language category (and how poorly they discriminate phonemes belonging to languages they are not exposed to) but also by their success at acquiring a variety of language skills during childhood (the native language neural commitment (NLNC) hypothesis; Kuhl, 2004). A finding that might be relevant for DD is that those children who were worse at perceiving native language phoneme contrasts showed less neural commitment and remained good nonnative language perceivers. These infants, in turn, did not develop language skills in a manner similar to that of those children who showed strong NLNC. Perhaps children at risk for DD also reveal less NLNC? In support of this assumption, our correlation results also link decreased native language representations and reading and writing skills in 9-year-old children. Furthermore, a number of studies have demonstrated that MMN-like responses to phonemes in infants at risk for DD were attenuated at birth and that these ERPs correlated later with language skills (Guttorm et al., 2010; Leppänen et al., 1999; Molfese, 2000; Molfese et al., 2001). These studies, however, have not addressed the question of how ERP responses in children with a genetic risk for DD are modulated by learning of native language representations. Thus, longitudinal studies investigating how children at risk for DD acquire native language representations might be relevant for unraveling the complexity of the etiology of DD. Furthermore, if native language representations are not formed in DD, this might be a very important area of focus for prevention and intervention programs aimed at improving literacy skills in DD.

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