Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes

Thomas Lachmann\textsuperscript{a,b,*}, Stefan Berti\textsuperscript{c}, Teija Kujala\textsuperscript{d}, Erich Schröger\textsuperscript{a}

\textsuperscript{a}Department of Psychology, University of Leipzig, Germany
\textsuperscript{b}Laboratory for Perceptual Dynamics, Brain Science Institute, Riken, Wako, Japan
\textsuperscript{c}Johannes Gutenberg-Universität Mainz, Germany
\textsuperscript{d}Helsinki Collegium for Advanced Studies and Cognitive Brain Research Unit at the Department of Psychology, University of Helsinki, Finland

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Abstract

The present study addressed auditory processing in 8–11-year-old children with developmental dyslexia by means of event-related brain potentials (ERP). Cortical sound reception was evaluated by recording N250 responses to syllables and tones and cortical sound discrimination by analyzing the mismatch negativity (MMN) to syllable and tone changes. We found that both cortical sound reception and sound discrimination were impaired in dyslexic children. The analysis of the data obtained from two dyslexic subgroups, Dyslexics-1 being impaired in non-word reading (or both non-word and frequent word reading) and Dyslexics-2 in frequent word reading but not in non-word reading, revealed that the MMN was specifically diminished in the latter group whereas it was normal-like in Dyslexics-1. However, no differences were found between these subgroups in sound reception as indicated by the responses elicited by the standard stimuli. These results show that different diagnostic subgroups of dyslexics have different patterns of auditory processing deficits as suggested by similarly impaired sound reception in both dyslexic groups and the sound-discrimination impairment specific to one of the groups.

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1. Introduction

Developmental dyslexia is defined as a specific disability in learning to read and to spell adequately despite at least normal intelligence, adequate instruction and socio-cultural opportunities, and the absence of sensory defects in vision and hearing (e.g.,
American Psychiatric Association, 1994). This definition rests, not upon etiologically grounded criteria, but upon a criterion of discrepancy between the reading performance as expected from measures of general intelligence, and the reading performance actually observed (discrepancy definition). In these terms, dyslexia is understood as a homogeneous developmental disorder. The abundance of partially contradicting experimental results, however, suggests that developmental dyslexia is in fact a polyetiological syndrome that is influenced by structural and functional characteristics of the central nervous system in interaction with exogenous factors (Becker et al., 2001, in press; Klein, 2002; Lachmann, 2002; Lachmann and Geyer, 2003). If so, then the identification of subtypes would have an arbitrative importance for specific educational treatment. Therefore, in the present study subfunctions of reading were studied in subgroups of developmental dyslexia as revealed from diagnostic tests.

2. Subgroups of developmental dyslexia

Dyslexics show different patterns of reading and writing failure (Bayliss and Livesey, 1985; Boder, 1973; Milne et al., 2003). Most common is the distinction between three subgroups; one failing in reading tasks requiring more analytic skills as, in its extreme form, is required in non-word reading; another group without such but failing in more holistic procedures assumed to be primarily applied in reading frequently used words; and finally a group that shows both patterns of problems. Such diagnostic clusters were initially purely descriptive. Nevertheless, it was concluded that they reflect distinctive underlying deficits: children with phonological processing deficits, called dysphonetics or phonological dyslexics (Boder, 1970; Flynn and Deering, 1989; McPherson and Ackerman, 1999; Milne et al., 2003; Vila Abad and Babero Garcia, 2002), or with a visual deficit slowing direct access to the lexicon, called dyseidetics (Boder, 1970; Milne et al., 2003). The mixed group, dysphoneidetics (Boder, 1970), is assumed to be affected by both deficits.

This etiological interpretation was motivated by neuropsychological findings (Coltheart, 1978; Coltheart et al., 1993; Derouesne and Beauvois, 1979; Marshall and Newcombe, 1973). Investigations of acquired dyslexia suggested that word reading is based on a Dual Route System; one of which, for high-frequency words, is a direct route from the visual word form to the word’s phonology and meaning, whereas for low-frequency words a second route to the lexicon proceeds via a grapheme-to-phoneme conversion rule in which individual letters are mapped onto phonological units before these are assembled into a phonological word form (Coltheart et al., 1993; Coltheart and Rastle, 1994; Ellis, 1984; Joubert and Lecours, 2000; Samuels et al., 1978). The latter system has to be activated during non-word reading. In reading meaningful text it is likely that both routes are always – or more or less – activated (Booth et al., 1999; Friederici and Lachmann, 2002). Nevertheless, it was concluded that problems in one or the other processing route may cause different reading failures. Thus, the performance in non-word reading vs. frequent word reading was suggested as a tool to differentiate between these groups (Coltheart, 1996; Stein, 2002).

Non-word reading reflects a certain degree of functional fragmentation (Lachmann, 2002) of the reading process. Even though top–down processes are also active in non-word reading (Harm and Seidenberg, 1999), it is mainly based on a bottom–up letter-by-letter desymbolization. Therefore, the conclusion that a failure in non-word reading characterizes some kind of a problem in grapheme-to-phoneme conversion is quite obvious. However, the interpretation that problems in frequent word reading are explicitly based on a visual2 deficit, that is, a problem to recognize a word as a visual Gestalt to enable a fast and direct access to the lexicon, is arguable. In fact, a limited ability in, for instance, reading aloud frequent

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1 Knowledge on acquired dyslexia should not be assigned directly to developmental dyslexia (c.f., Lachmann, 2002). Nevertheless, there is evidence for such more or less distinct routes in normal reading (Cohen et al., 2000; Fiebach et al., 2002) and for some kind of a “visual word form system” in the brain (Warrington and Shallice, 1980).

2 From our point of view, for this particular causal interpretation the term visual should not be used as an opposite to phonological or linguistic. Recognizing a word Gestalt is always a linguistic act and is based on visual functions that are specific for reading from a rather early level. Therefore, the term orthographic deficit or word recognition deficit should be preferred.
words from a list may also be explained by a phonological deficit. From a number of studies (Hagoort et al., 1999; Price et al., 1994; for review see Friederici and Lachmann, 2002), we can conclude that the lexical access requires the activation of what we may call here a phonological word Gestalt. This activation may be deficient while the visual Gestalt recognition is not. Thus, children without problems in non-word reading but in frequent word reading may suffer from a phonological deficit. Therefore, instead of assuming a visual recognition deficit in dyslexics, it could alternatively be argued that the failure in both non-word and frequent word reading may be caused by a phonological processing deficit. However, while the first one is specific to a visual presentation of phonological information, by requiring a graphemeto-phoneme convention, the latter one is not.

A considerable number of authors doubt that there is any visual deficit in developmental dyslexia (Snowling, 2001; Vellutino et al., 1972). In contrast, others found evidence for a non-language-specific deficit of visual information processing in at least some dyslexics (for review see Lovegrove, 1993). However, visual deficits have rarely been studied systematically in diagnostic subgroups. For instance, Borstig et al. (1996) measured contrast sensitivity in two subgroups of dyslexia, and showed that not the dyseidetics (as may be expected by the term), but the dysphoneidetics differ from controls in such a non-linguistic task. A similar result was found by Slaghuis and Ryan (1999)—a reduction in contrast sensitivity at low spatial frequencies in dysphoneidetics and dysphonetics but not in dyseidetics. Dysphoneidetics were also identified to have longer visible persistence and a reduction in sensitivity for coherent motion as compared to controls. Taken together, these results suggest that dyseidetics do not have a visual deficit and it seems doubtful that their problems in word recognition are due to any kind of a visual deficit. The question remains, however, whether their problems are instead caused by phonological processing deficits. In fact, Milne et al. (2003) found that dyseidetics especially fail in phonological decoding tasks. However, their interpretation is that dyseidetics have fewer lexical representations of visually similar words.

In the present study, phonological processing was compared between controls and two subgroups of dyslexics – those with and those without problems in non-word reading as compared to a reference population – using a passive sound discrimination task.

3. Sound discrimination in dyslexia

Phonological discrimination is known to be an indicator for the quality of phonological coding/decoding (Cornelissen et al., 1996; Fox, 1994; Fuchs and Lachmann, 2003; Manis et al., 1997; Werker and Tees, 1987). However, there is a serious discourse about whether phonological deficits are due to a more general, that is, a non-linguistic, auditory low-level dysfunction, such as a temporal processing deficit, either of general nature (Facoetti et al., 2003; Farmer and Klein, 1995; Klein, 2002; Stein, 2002; for a review see Habib, 2000) or specific to the auditory domain (Kujala, 2002; Rey et al., 2002; Tallal, 1980, 1984). According to a number of authors (Farmer and Klein, 1995; Helenius et al., 1999; Tallal, 1980; Tallal et al., 1995), low-level processing deficits cause problems in discriminating rapid temporal changes (as are typical of speech), and thus, disturb the adequate development of phonological codes from an early age in childhood. Other authors failed to find low-level auditory deficits in dyslexics (Chiappe et al., 2002; Hill et al., 1999, see Snowling, 2001 or Studdert-Kennedy and Mody, 1995, for a review).

Most of these studies are behavioral and therefore can have only restricted value in deciding whether the revealed phonological problems are the result of a low-level deficit (Breznitz and Misra, 2003). For this reason, in the present study both phonological and non-phonological auditory discrimination skills are tested in subgroups of dyslexics and controls using event-related potentials (ERPs) recorded from the scalp by the electroencephalogram (EEG), a non-invasive technique allowing one to specify temporal and spatial components of the information processing before the response to a given task is made.

In a number of studies, latencies and amplitudes of different ERP potentials were found to discriminate between dyslexics and controls (Breznitz and Leikin, 2001; Leppänen et al., 1997; McPherson and Ackerman, 1999; Vila Abad and Babero Garcia, 2002). For instance, Breznitz and Meyler (2003) found group differences in oddball tasks, where the ERPs to so-called deviant sounds, presented among a row of
standards, were compared between groups. This can be interpreted as evidence for a low-level auditory deficit in dyslexics (Klein, 2002), or as an asynchronous extraction of auditory and visual codes (Breznitz and Meyler, 2003); both would result in faulty phonological codes.

The components of an ERP, especially the early ones, reflect the neural correlates of reception and encoding of a stimulus. In contrast, sound discrimination is a cognitive act, that is, stimuli have to be compared. A paradigm which was developed in order to measure the neural cognitive, but pre-attentive processes underlying sound discrimination is the so-called mismatch negativity (MMN) paradigm (Naätänen et al., 1978; Naätänen, 1992, 2000; Schröger, 1997, 1998). The MMN is an evoked cortical potential that reflects the outcome of an automatic comparison between acoustic stimuli when a deviant is presented randomly at a certain rate among repetitive standard stimuli. The negativity results from the difference between the ERP evoked at about 100–250 ms after deviant-stimulus onset and that evoked by the standard stimulus.

During the last decades, the MMN was observed to be elicited by deviants differing from the standard in duration, pitch, frequency, intensity (see Naätänen, 1992, for an overview), in more complex features such as tone patterns (Kujala et al., 2000), phonemes (Shtyrov et al., 2000; Winkler et al., 2003), common invariant patterns shared by a number of acoustically varying sounds (Naätänen et al., 2001), by words (Korpiilahdi et al., 2001) and even by grammatical structures (Pulvermüller and Shtyrov, 2003). Since the MMN occurs without paying attention to the input, this method is quite expedient to measure automatic discrimination processes directly in patients (Ilvonen et al., 2001; Naätänen, 2003), young children (Cheour et al., 2000; Uwer and von Suchodoletz, 2000) and even infants (Alho and Cheour, 1997; Cheour et al., 2000; Friederici et al., 2002; Naätänen, 2000, 2003) for all of which the measurement of behavioral responses is rather constricted. Therefore, the MMN may be a suitable tool to compare the quality of the representation of speech and non-speech stimuli in dyslexic school children and controls in order to decide whether the deficit underlying the reading problems is speech-specific or not and whether the deficit is pre-attentive or at a higher level.

The MMN has already been applied in this respect (Hugdahl et al., 1998; Kujala, 2002; see Kujala and Naätänen, 2001, for a review). One of the first studies was carried out by Schulte-Körne and his colleagues (Schulte-Körne et al., 1998), who compared syllable (/da/ vs. /ba/) and tone (1000 vs. 1050 Hz) discrimination with the MMN in dyslexic teenagers and controls. They found that, whereas the MMN amplitude elicited by the tone deviant did not significantly differ between the dyslexics and controls, the MMN elicited by the syllable deviant was diminished in dyslexics. They interpreted their results in terms of a speech-specific pre-attentive processing deficit in dyslexics. It should be mentioned, however, that this interpretation is restricted, because the stimuli do not exclusively differ in respect of their phonological content.

At about the same time, Baldeweg and colleagues (Baldeweg et al., 1999) found a diminished MMN for tone deviants in young dyslexic adults. In their study, the MMN was different between dyslexics and controls for pitch deviants (standard: 1000 Hz, deviants: 1015, 1030 and 1060, but not for 1090 Hz), which suggests a non-speech auditory deficit in dyslexics underlying their phonological processing deficits. The group difference was found to be larger the smaller the difference between the deviant and standard was. The MMNs elicited by duration differences, however, did not differ between the groups.

Further group differences of various MMN parameters were found either in favor of the speech-perception deficit hypothesis (Csépe et al., 1998), or in favor of a basic auditory dysfunction in dyslexics (Kujala, 2002; Kujala et al., 2003). Maurer et al. (2003), for instance, investigated kindergartners at familial dyslexia risk. They found late MMN group differences for tone frequency deviance (standard: 1000 Hz, deviants: 1015, 1030 and 1060 Hz) as well as for phoneme deviance (standard /ba/, deviants: /ta/ and /da/).

3 Note, however, that the samples in Maurer et al. are not comparable to the ones in the other studies reported; the authors announced a follow-up study in order to check whether the differences are specific to those children who will later be diagnosed as dyslexics.
4. Experiment

The reviewed MMN studies revealed inconsistent results. Besides differences in methodology (e.g., different stimuli and MMN parameters) and samples (adults, children, children at risk, discrepancy criterion), in our view, one major reason for this inconsistency is that diagnostic subgroups are not considered. Baldeweg et al. conducted analyses of correlations between parameters of the MMN and error rates in word and non-word reading tests. These diagnostic data, however, were not used to perform subgroup-specific analyses of the MMN parameters. In contrast, in the present study, we investigated whether sounds are differently discriminated by subgroups of dyslexic children. We did this by comparing the MMNs of those children who had deficits in at least non-word reading (a task that requires a grapheme–phoneme conversion technique) with those who failed in frequent word reading only (a task that may be solved on the basis of alternative strategies such as an identification of word as Gestalt followed by a direct access to the lexicon and which may be merged directly with a phoneme Gestalt). Moreover, we analyzed the ERPs evoked by the standard stimuli. In the participating children, both kinds of stimuli are expected to evoke an ERP with a N250 peak (Courchesne, 1978; Ceponiene et al., 2001), which reflects more basic auditory processing and sound reception—not identical, but to some extent comparable to the N100 in adults (Ceponiene et al., 2001; Shafer et al., 2000). The aim is to test whether both subgroups have deficits in sound discrimination and if so, to what extent these deficits differ between the groups.

5. Method

5.1. Participants

There was a total of 28 children participating in this study; 16 dyslexic children (8 female; mean age 9.3, SD=0.5; mean IQ 96, SD=19) and twelve non-dyslexic (controls) children (7 female; mean age 9.3, SD=0.6; mean IQ=104, SD=11). All children had normal or corrected-to-normal vision and normal hearing, and were right-handed as measured with a handedness test, except one dyslexic child who was ambidextrous. There were no significant differences between the groups in age, grade or non-verbal intelligence. The children received toys, each equivalent to 10–15 EUR, for their participation. The children, their parents and teachers, the federal office of education and the ethic committee of the University of Leipzig gave their agreement to this study.

5.2. Diagnosis of dyslexia

Dyslexic children were enrolled in a special training class for dyslexic children in Leipzig for the first or second year of a 2-year program4 during Grade Level 3. In this respect, a discrepancy-based diagnosis of developmental dyslexia had previously (either 3 or 15 months before EEG recording) been given to these children by a specialist team using the test battery by Weigt (1980) during Grade 2 of primary school. The examination included reading and spelling for both contextualized and isolated letters and words, phoneme segmentation, visual recognition, phonological and visual differentiation (Breuer and Weuffen, 1995), as well as a number of test lessons. Furthermore, physical development and sensory functioning were tested by an ophthalmologist and an otolaryngologist. Motivational, attentional, emotional, educational and social factors that may have influence on the learning process were also considered. The children of the control group were obtained from the third and the fourth grade of the same school in Leipzig from which the dyslexic children were recruited.

5.3. Reading tests

The diagnosis described above was given to each child individually according to a discrepancy between his/her reading performance as measured by standardized reading tests, and general cognitive abilities as measured by a standardized intelligence test (for a discussion on the discrepancy criterion see Jiménez

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4 For these children Grade 3 last 2 years in order to have the opportunity to increase the amount of German lessons without neglecting other subjects. The additional German lessons (as well as the other subjects) have the same curriculum as in regular classes. The education, however, focuses more on basic reading skills usually trained in Grades 1 and 2.
Gonzales, 2002; Lachmann, 2002; Stanovich, 1991). No further distinction has been made between possible subgroups and all children received the same education. In order to validate this previously given diagnosis and to differentiate on which reading deficits—either more analytic, more holistic or both—the diagnosis is based on, we tested all children (dyslexics and controls) again and individually, 1 to 6 days before EEG recording. For this purpose, the Raven Progressive Matrices test (Heller et al., 1998) and two subtests of the Salzburger Lese-Rechtschreibtest (SLR, Landerl et al., 1997) were used, one testing the ability of reading frequently used words (holistic reading skills) and the other testing non-word reading (analytic reading skills), both by means of reading time, which was found to discriminate better between the groups than error rate (c.f. Landerl and Wimmer, 2000; Landerl et al., 1997). One child previously diagnosed as dyslexic had IQ=68 and therefore, was excluded from further examination. All other children had at least normal intelligence and were, according to the discrepancy definition (e.g., American Psychiatric Association, 1994), expected to read normally. Each child’s performance in both reading tests was compared to that of the corresponding reference population of the SLR test. As criterion of discrepancy a performance below 2 SD (percentage rank <3) of that of the reference population in at least one of the two subtests was used. There were two children previously diagnosed as dyslexics who were excluded from further analyses because they showed normal performance in both tasks. To serve as a control participant, a child had to perform within the norms of the reference population in both tasks (percentage rank >17; <1 SD). Their diagnosis of dyslexia is based on a failure in frequent word reading (FWR), as expressed by a reading time higher than 2 SD over the average of the reference population (percentage rank <3). This subgroup will be termed Dyslexics-2. According to many authors (e.g., Boder, 1970), their reading problems are caused by other than phonological deficits (more related to the visual domain) and therefore, they are expected to show no difficulties in phonological discrimination.

5.4. Diagnostic subgroups of dyslexics

Diagnostic subgroups were differentiated according to which of the two tests were discrepant. There were eight children (five female, mean age=9.4, SD=0.6; IQ=98.9, SD=23) with a reading time higher than 2 SD (percentage rank=3) over that of the reference population in non-word reading (NWR) or both tests, and were therefore classified as having at least phonological problems. This subgroup of dyslexics will be termed as Dyslexics-1. In the literature (e.g., Baldeweg et al., 1999), it is often argued that these children should have problems in phoneme discrimination. The other eight children (three females, mean age=9.1, SD=0.4; IQ=93, SD=14) performed NWR without difference from the reference population (percentage rank >17; <1 SD). Their diagnosis of dyslexia is based on a failure in frequent word reading (FWR), as expressed by a reading time higher than 2 SD over the average of the reference population (percentage rank <3). This subgroup will be termed Dyslexics-2. According to many authors (e.g., Boder, 1970), their reading problems are caused by other than phonological deficits (more related to the visual domain) and therefore, they are expected to show no difficulties in phonological discrimination.

5.5. Stimuli and procedure

There were two stimulus conditions; one including professional female spoken digitized consonant–vowel syllables /ba/ and /da/ as stimuli, and the other one including 700-Hz and 770-Hz sinusoidal tones as stimuli. Tones and the syllables were 385 ms long and were presented with a fixed ISI of 515 ms (SOA=900 ms). In both conditions, one stimulus was used as a standard while the other stimulus was used as a deviant. The probability for the deviant stimuli was 12% in all blocks and conditions. In half of the blocks the deviant stimuli were the /da/ and the 770-Hz tone while the /ba/ and the 700-Hz tone served as standard stimuli, and vice versa in the other half of the blocks. Each block started with five standard trials which were discarded from the analysis, since the first stimuli elicit considerably larger exogenous responses than the following ones (Näätänen and Picton, 1987). There was a minimum of three standards presented before a deviant. The complete session took about 1 h plus varying preparation time. During the recording, the participants were watching a self-selected adventure movie without sound.
The stimuli were presented binaurally through head phones which reduced background noise at the children’s ears with an intensity of approximately 70 dB. The children were told that they could ignore the sounds.

5.6. EEG recording

The EEG was recorded with MES amplifiers from F3, Fz, F4, Cz, Pz of the 10–20 system and left and right mastoids, referred to the nose (0.1–80-Hz band pass and 50-Hz notch filter, sampling rate 250 Hz). The electrodes were mounted in an elastic cap (FMS). Electro-occulogram (EOG) was recorded from above and below the right eye (vertical EOG) and the outer canthus of each eye (horizontal EOG). The EEG was offline filtered with a 1–20-Hz band pass filter. Epochs with extensive EOG activity (voltage changes of more than 100 µV) were excluded from the subsequent averaging procedure. The ERPs were computed separately for the standard and deviant stimuli in each condition within a time window of −100 to 400 ms relative to stimulus onset with a pre-stimulus interval from −100 ms to stimulus onset serving as a baseline. Additionally, the single participants’ ERPs were 10-Hz low pass filtered (c.f., Sinkkonen and Tervaniemi, 2000).

Before the data quantification, the ERPs were re-referenced to the average of the left and right mastoids. The MMN was quantified for each condition from difference waves that were obtained for each group by subtracting the ERPs to the standard stimuli from the ERPs to the deviant stimuli. After visual inspection of the frontal electrodes, the MMN amplitude was measured as the mean amplitude within a time window of 100 ms around the grand-mean peak latencies (this is, plus 50 ms and minus 50 ms) separately for each condition and the a priori groups (dyslexic group, control group). For the syllable condition, the windows were as follows: 98–198 ms for the dyslexic group, and 122–222 ms for the control group. For the tone condition, a window of 158–258 was used for dyslexic group, and 154–254 ms for controls. In addition, to assess the N250 responses (Ceponiene et al., 2001) elicited by the standard stimuli, mean ERP amplitude within a fixed time window of 200–300 ms after stimulus onset was used in all conditions and groups because there were no remarkable grand-mean peak latency differences between them.

6. Results

The presence of the MMN and the standard N250 at all frontal electrodes and conditions were determined by using a series of t-tests, comparing the amplitude values against zero. Including all frontal electrodes analyses of variance (ANOVA) were run for MMN and standard ERP amplitudes, including the two within-subject factors Electrode (F3, Fz, F4) and stimulus (tones vs. syllables) and the group factor (controls, Dyslexics-1, Dyslexics-2), followed by Bonferroni post-hoc analyses and analyses of contrasts. The Greenhouse–Geisser correction was used to calculate the level of significance, while the F-values report the uncorrected degrees of freedom.

6.1. MMN

The MMNs were calculated for the frontal electrodes, F3, Fz and F4 (cf., Näätänen, 1992). The mean MMN for controls and the two dyslexic subgroups are displayed in Table 1. In the control group, an MMN was significantly elicited by tone deviants, \(t(11)=-4.17\) to \(-4.68, p<0.01\), at all frontal electrodes. For

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Amplitude means and standard deviations (µV) of the MMN for the two conditions in controls, Dyslexics-1 and Dyslexics-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sinus-tone condition</strong></td>
<td><strong>Syllable condition</strong></td>
</tr>
<tr>
<td>F3</td>
<td>Fz</td>
</tr>
<tr>
<td>Controls</td>
<td>−2.58** (1.96)</td>
</tr>
<tr>
<td>Dyslexics-1</td>
<td>−1.82* (1.93)</td>
</tr>
<tr>
<td>Dyslexics-2</td>
<td>−1.20 (2.27)</td>
</tr>
</tbody>
</table>

Level of significance: (*) \(p<0.1\); *\(p<0.05\); **\(p<0.01/p<0.001\).
the syllables, the MMN was found to be significant for FZ, \(t(11)=2.52, p<0.05\), and for F4, \(t(11)=-3.68, p<0.01\). A similar pattern was found for Dyslexics-1; the MMN was significantly elicited by the deviant for both the tone stimulus, \(t(7)=-2.67–4.57, p<0.01\) (\(p<0.05\) for F3), and the syllable stimulus, \(t(7)=-2.9–3.9, p<0.01\), at each of the frontal electrodes, except for the syllables at F3. In contrast, in Dyslexics-2, for none of the stimulus conditions was an MMN found at any frontal electrode.

A 3×2×3 ANOVA using the within-subject factors electrode, stimulus and the between-subject factor group revealed a main effect of stimulus, \(F(1, 25)=7.75, p<0.01\), and a group effect, \(F(2, 25)=5.01, p<0.01\). No interaction was found. The effects are visualized in Fig. 1. Across frontal electrodes, in all groups, the MMN was larger for tones than for syllables (see Table 1). The group effect was evaluated by Bonferroni and Dunnett post-hoc analyses, which revealed that the MMN amplitudes are significantly smaller in Dyslexics-2 as compared to controls (\(p<0.01\)) and as compared to Dyslexics-1 (\(p<0.05\)), respectively, while the Dyslexics-1 and controls do not differ. Comparing the two dyslexic groups combined (contrasts) against controls, however, leads to a significant difference (\(p<0.05\)), as well as comparing controls and Dyslexics-1 combined against Dyslexics-2 (\(p<0.01\)).
6.2. ERPs evoked by the standard stimuli

In the controls, the standard stimuli evoked a significant N250 in the tone condition, \( t(11) = -28.0 \) to \(-31.5, p<0.001\), and the syllable condition, \( t(11) = -10.5 \) to \(-11.6, p<0.001\). In Dyslexics-1, \( t(7) = -4.75 \) to \(-5, p<0.01\), and in Dyslexics-2, \( t(7) = -3.5 \) to \(-3.6, p=0.01\) the N250 ERP was significant at each of the frontal electrodes for the tone condition. For the syllables, the standards evoked significant ERPs in

Table 2
Amplitude means and standard deviations (\( \mu V \)) for the ERPs for the two conditions in controls, Dyslexics-1 and Dyslexics-2

<table>
<thead>
<tr>
<th></th>
<th>F3</th>
<th>Fz</th>
<th>F4</th>
<th>F3</th>
<th>Fz</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sinus-tone condition</strong></td>
<td><strong>F3</strong></td>
<td><strong>Fz</strong></td>
<td><strong>F4</strong></td>
<td><strong>F3</strong></td>
<td><strong>Fz</strong></td>
<td><strong>F4</strong></td>
</tr>
<tr>
<td>Controls</td>
<td>-9.65** (1.19)</td>
<td>-10.00** (1.26)</td>
<td>-10.00** (1.10)</td>
<td>-6.48** (2.13)</td>
<td>-6.88** (2.10)</td>
<td>-6.75** (2.01)</td>
</tr>
<tr>
<td>Dyslexics-1</td>
<td>-6.64** (3.95)</td>
<td>-6.88** (3.85)</td>
<td>-6.99** (4.04)</td>
<td>-3.25** (1.92)</td>
<td>-3.28** (1.81)</td>
<td>-3.22** (1.77)</td>
</tr>
<tr>
<td>Dyslexics-2</td>
<td>-6.07** (4.94)</td>
<td>-6.06** (4.71)</td>
<td>-6.03** (4.80)</td>
<td>-3.57* (3.81)</td>
<td>-3.43* (3.80)</td>
<td>-3.28* (3.54)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Syllable condition</strong></th>
<th><strong>F3</strong></th>
<th><strong>Fz</strong></th>
<th><strong>F4</strong></th>
<th><strong>F3</strong></th>
<th><strong>Fz</strong></th>
<th><strong>F4</strong></th>
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Level of significance: *\( p<0.05 \); **\( p<0.01/p<0.001 \).

Fig. 2. Event-related potentials to standard syllables and tones for controls, Dyslexics-1 and Dyslexics-2.
Dyslexics-1, \( t(7) = -4.8 \) to \(-5.1 \), at the 1% level of significance, whereas, in Dyslexics-2, the ERPs reached only the 5% level, \( t(7) = -2.6 \) (see Table 2).

A 3×2×3 ANOVA using the factors electrode, stimulus and group revealed a main effect of stimulus, \( F(1, 25) = 67.84, p < 0.001 \), and a group effect, \( F(2, 25) = 4.99, p < 0.01 \). No significant interaction was found, but there were weak interactions (\( p < 0.1 \)) between electrode and group and between electrode and stimulus. The effects are visualized in Fig. 2. The group effect was evaluated by Bonferroni and Dunnett post-hoc analyses, which revealed that the standard ERP amplitudes are significantly smaller in both dyslexic groups, Dyslexics-1 (\( p < 0.05 \)) and Dyslexics-2 (\( p < 0.05 \)) as compared to controls, respectively, while the dyslexic groups did not differ. Comparing the two dyslexic groups combined contrasting against controls leads to a significant difference (\( p < 0.01 \)), while testing each dyslexic group against the other two combined, respectively, did not lead to significance.

7. Discussion

The present study addressed cortical sound discrimination (MMN) and sound reception (ERPs elicited by standard stimuli) for tones and syllables in dyslexic children taking into account diagnostic subgroups; Dyslexics-1 showing an at least 2 SD higher reading time in the subtest non-word reading (NWR) or both NWR and frequent word reading (FWR) and Dyslexics-2 showing an at least 2 SD higher reading time in FWR but without deficit in NWR as compared to the reference population in the SLRT, respectively. Significant MMNs were found for controls and Dyslexics-1 in both the tone and the syllable condition. In contrast, Dyslexics-2 had no significant MMN for either stimulus conditions. The MMN was found to be smaller for syllables as compared to tones. For both stimulus conditions, the MMN was smaller in Dyslexics-2 as compared to Dyslexics-1 and controls, while the latter two did not differ.

The results confirm the importance of the consideration of diagnostic subgroups in dyslexia. It was shown that only one of the subgroups displays an altered MMN while the other shows a normal-like MMN pattern. Importantly, the difference in one subgroup (Dyslexics-2) was shown to be strong enough to generate a weak but statistically significant group main effect in a post-hoc test of contrasts between controls and dyslexics as a whole group. In that respect, the results can be compared to previous studies which investigated MMN differences between dyslexics and controls.

Whereas the group effect in the syllable condition is consistent with the finding of Schulte-Körne et al. (1998), who also showed diminished MMN to /ba/-/da/ stimuli in dyslexics, the finding for the tone condition is not. One reason may be seen in methodological differences. In Schulte-Körne et al., the standard was a 1000-Hz tone while we used a 700-Hz tone. On the other hand, Schulte-Körne et al. used a deviant of 5% higher frequency, whereas in the present study the deviant was of 10% higher frequency, which makes a group difference more likely for the first study. Another difference between the studies is that the participants in Schulte-Körne et al. were much older. On the other hand, Baldeweg et al. (1999) found tone MMN group differences for even older participants. There, however, group effects were evident for tone deviants of 1.5%, 3%, and 6% higher frequency than the standard of 1000 Hz (the same standard as the one in Schulte-Körne et al.), whereas in the condition closest to ours, that is, their 9% pitch difference, there was no group difference.

Besides these and other methodological differences, however, the present results show that the reason for contradictory results in the literature may be the neglect of diagnostic subgroups. In the present study, it was found that only Dyslexics-2 show differences in the discrimination of sounds as expressed by a diminished MMN for tones and syllables. At the first glance, this may suggest a low-level auditory deficit in these children. However, this conclusion can only be drawn with restriction, because the tones and the syllables do not solely differ in respect of their phonological content but also in their physical structure (as in Schulte-Körne et al. and comparable studies). Thus, the results for tones and for syllables could, in principle, represent independent processing deficits in dyslexia; an auditory one, as expressed by the tone difference, and a phonological one, as specific for the syllable stimuli.
The MMN is pre-attentive, but the comparison is based on memory traces, and thus on learned representations. In contrast, the early ERPs represent stimulus reception. As already mentioned, children’s auditorially evoked brain responses differ from that of adults (Cepoiniene et al., 2001; Ponton et al., 2000; Shafer et al., 2000). The N250 of the standard ERPs was analyzed as representing low-level auditory processing, that is, sound reception comparable to the N100 in adults.

The ERPs to the standard stimuli were found to be significant for both stimulus conditions in controls and both dyslexic subgroups. The amplitudes were higher for tones than for syllables in all groups and conditions. A group main effect, but no interaction was found. Controls differed from Dyslexics-1 and from Dyslexics-2, whereas the dyslexic groups did not differ from one another, suggesting a similar deficit in these two groups. This result suggests a low-level auditory processing deficit in dyslexic children for simple tone sounds as well as for rather complex sounds such as syllables. This pattern of the group effect contrasts to that found for the MMN.

In the following, the pattern of the MMN and ERP results are discussed separately for each subgroup. By definition (American Psychiatric Association, 1994), the diagnosis of developmental dyslexia was given to each child according to an individually measured discrepancy between his/her reading performance in a standardized reading test and the child’s general cognitive abilities. This discrepancy was defined as an at least 2 SD higher reading time in at least one of two subtests of the SLRT while having normal or above-average intelligence, both compared to the reference population. According to which subtest the discrepancy was found on, two subgroups were differentiated.

7.1. Dyslexics-1

The pattern of their reading problems suggest that Dyslexics-1 have particularly problems in analytic reading skills, which primarily require a grapheme-to-phoneme conversion and therefore, these children fail especially in reading context-free words, rare words, or – as applied here – in reading non-words (NWR). These problems, however, make them likely to fail in other reading tasks as well, such as in frequent word reading (FWR). This may be explained as a secondary symptom; it is very plausible that children with problems in analytic skills will have considerably less reading-related input—they will read less than others and therefore, visual and phonological Word–Gestalt recognition, phonological awareness and other determinants of reading skills may be impaired as well (depending on education, social background and motivation). This may be the reason why many of these pupils have problems in both NWR and FWR.

The analysis of MMN elicited by syllables and tones in this group of dyslexics revealed no differences from controls. This group seems to have no problems in sound discrimination, not for tones, nor for phonological stimuli. At first glance, this seems to be a contradiction, because this group is often termed “dysphonetics” and is assumed to suffer from phonological processing deficits. However, this assumption is solely based on the fact that they fail in a task in which phonological skills are definitely needed, that is, NWR. Why, then, do they have no problems in pre-attentive sound discrimination? An answer could be that this group is not primarily characterized by a general phonological deficit but by a very specific one, that is, the conversion from grapheme to phoneme. This specific deficit makes them fail in more analytic reading demands. In contrast, the task in the present experiment was to discriminate sounds presented auditorily—no grapheme-to-phoneme conversion is needed and therefore, these children have no problems in the discrimination.

This assumption implies that Dyslexics-1 may perform worse than controls only in those experiments in which the function under investigation involves, either explicitly or implicitly, the processing of graphemic information. Support for such an interpretation was found by Lachmann (2003) who investigated the same participants as those of the present study using auditory and visual presentation of speech and non-speech items in behavioral matching tasks. He found that Dyslexics-1 differ from controls only in those conditions in which graphemic and phonological information had to be merged in order to solve the
task. In contrast, he found dramatically increased response times in Dyslexics-2 independently of the domain in which the items were presented.

7.2. Dyslexics-2

The children defined as Dyslexics-2 did not show any problem in analytic reading demands. They read, for instance, non-words as fast and accurately as the reference population. This suggests that these children do not have particular problems in grapheme-to-phoneme conversion and therefore, that they may have other than phonological deficits. In this context, their impairment in FWR reading is explained in terms of a problem in recognizing frequently used words as visual Gestalts to enable a fast and direct access to the lexicon.

In the present experiment, it was this subgroup in which deficits in sound discrimination, for both tones and syllables, were evident. Again, these results seem opposite to what, according to the mainstream, would be expected. However, it should also be noted that in the present study, the reading task, in which this group failed, was to read words aloud. As a matter of course, this task requires phonological skills – “naming the word” – and therefore, a failure may also be due to a deficit in activating what we may call a phonological Gestalt instead of a deficit in visual Gestalt recognition. In this respect, the present results could be understood as a deficit in activation of phonological Gestalts in order to access the lexicon. Even though we did not use words in the EEG experiment, the syllables represent minimal versions of such phonological Gestalts (Ashby and Rayner, 2004). However, the sound discrimination in this group was also deficient for tones. Additionally, the reception of auditory information, for tones and syllables, was found to be impaired, as revealed from ERP analyses. This may suggest a low-level processing deficit as the basis for a phonological deficit. However, the low-level deficit may also be independent of the stimulus domain, and the phonological vs. the low-level differences may reflect parallel deficits.

It should be mentioned, however, that there may be some alternative explanations for the null MMN in Dyslexics-2. As one reviewer argued, since we used quite large frequency deviations with rather intense stimuli, there may be a change in the N1 amplitude that will carry through to the difference waveform. Additionally, even though the participants were instructed to ignore the stimuli, there is still a risk of some N2b activity which could have been picked up by the rather broad window used.

In summary, the present study demonstrated the relevance of diagnostic subgroups for experimental research on developmental dyslexia. It was shown that diagnostic subgroups of dyslexics have different patterns of auditory processing deficits, as suggested by similarly impaired sound reception in the two dyslexic subgroups and the sound discrimination impairment specific to one of the groups. School children with increased reading times for non-words, usually termed dysphonetics or dysphoneidetics, were found to be impaired in cortical sound reception for tones and syllables. This was suggested to reflect a low-level processing deficit that specifically disrupts an adequate grapheme-to-phoneme conversion. Children exclusively failing in reading frequently used words were found to be impaired in both pre-attentive sound discrimination and reception, for both tones and syllables. It was concluded that a deficit in the activation of phonological Gestalts may prevent fast access to the lexicon and thus cause problems in FWR. This phonological deficit was suggested to be based on a low-level processing deficit, either specific to the auditory domain or of a general nature (further experiments have to be conducted to answer this question).

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5 The exact nature of the deficit in this group cannot be assessed by the present data. All together, however, it seems in fact likely that this group (which may even not be a homogeneous one) is characterized by a low-level deficit underlying their problems in analytic reading skills (specifically in NWR), which becomes present when phonological information is presented visually. The failure in analytic reading skills has its secondary impact of the quality of phonological representations in the lexicon, and tertiary – due to a decreased reading motivation and experience – on visual word recognition skills. These secondary and tertiary deficits may, depending on individual and educational conditions, more or less affect the performance in FWR. These speculative conclusions, however, have to be proven in further experiments.

6 This would even hold for silent reading; from a number of studies (Hagoort et al., 1999; Price et al., 1994; for review see Friederici and Lachmann, 2002) we can conclude that the lexical access requires the activation of a phonological word Gestalt.
It should be emphasized that we do not suppose that there are only two subgroups in dyslexia. We identified two subgroups according to a rough distinction of patterns of reading problems. The identification of deficient subfunctions in dyslexics has a high practical relevance. The identification of deficient function can take place even before learning to read, which should be considered as very important, since we know that an intervention is most helpful when it is started early (e.g., Marx, 1992 for a review) and may also be possible by training deficient subfunctions (Kujala, 2002). In general, the present results underline the necessity to combine neuroscience and education and to use our increased knowledge/understanding of brain functions in order to explore educational questions (Goswami, 2004).

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