Auditory sensory deficits in developmental dyslexia: A longitudinal ERP study


Published in:
NeuroImage

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
Auditory sensory deficits in developmental dyslexia: A longitudinal ERP study

Gabor Stefanics a,b, Tim Fosker a,c, Martina Huss a, Natasha Mead a, Denes Szucs a, Usha Goswami a,*

a Centre for Neuroscience in Education, Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, UK
b Institute for Psychology, Department of Experimental Psychology, Hungarian Academy of Sciences, 83-85 Szondi u., Budapest 1068, Hungary
c Centre for Neuroscience in Education, Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, UK

A R T I C L E   I N F O

Article history:
Received 15 November 2010
Revised 28 February 2011
Accepted 3 April 2011
Available online 12 April 2011

Keywords:
Developmental dyslexia
ERP
Maturation
MMN
Rise time
Intensity
Duration
P1-N1c-N2

A B S T R A C T

The core difficulty in developmental dyslexia across languages is a "phonological deficit", a specific difficulty with the neural representation of the sound structure of words. Recent data across languages suggest that this phonological deficit arises in part from inefficient auditory processing of the rate of change of the amplitude envelope at syllable onset (inefficient sensory processing of rise time). Rise time is a complex percept that also involves changes in duration and perceived intensity. Understanding the neural mechanisms that give rise to the phonological deficit in dyslexia is important for optimising educational interventions. In a three-deviant passive 'oddball' paradigm and a corresponding blocked 'deviant-alone' control condition we recorded ERPs to tones varying in rise time, duration and intensity in children with dyslexia and typically developing children longitudinally. We report here results from test Phases 1 and 2, when participants were aged 8–10 years. We found an MMN to duration, but not to rise time nor intensity deviants, at both time points for both groups. For rise time, duration and intensity we found group effects in both the Oddball and Blocked conditions. There was a slower fronto-central P1 response in the dyslexic group compared to controls. The amplitude of the P1 fronto-centrally to tones with slower rise times and lower intensity was smaller compared to tones with sharper rise times and higher intensity in the Oddball condition, for children with dyslexia only. The latency of this ERP component for all three stimuli was shorter on the right compared to the left hemisphere, only for the dyslexic group in the Blocked condition. Furthermore, we found decreased N1c amplitude to tones with slower rise times compared to tones with sharper rise times for children with dyslexia, only in the Oddball condition. Several other effects of stimulus type, age and laterality were also observed. Our data suggest that neuronal responses underlying some aspects of auditory sensory processing may be impaired in dyslexia.

© 2011 Elsevier Inc. All rights reserved.

Introduction

Developmental dyslexia is a disorder of learning that affects approximately 7% of children and can significantly impair educational outcomes and eventual quality of life. Dyslexia is found across languages irrespective of the orthography used, and irrespective of the complexity of the phonological structures of spoken word forms (Ziegler and Goswami, 2005; Ziegler et al., 2003). The core cognitive problem across languages is accepted to be a deficit in phonological representation (Swan and Goswami, 1997; Snowling, 2000; Ziegler and Goswami, 2005). However, relatively little is currently understood about underlying brain mechanisms. A better understanding of the core neural deficits would enable more effective interventions. One possibility that has been widely investigated at the sensory level is that children with dyslexia have auditory processing difficulties (e.g., Tallal, 1980; Witton et al., 1998; Goswami et al., 2002). One auditory sensory deficit that is found in children with dyslexia across languages is inefficient processing of the rate of change of amplitude envelopes (also called rise time; Goswami et al., 2002, 2010a; Hämäläinen et al., 2009; Muneaux et al., 2004; Richardson et al., 2004; Surányi et al., 2009). Here, we extend the investigation of rise time processing in dyslexia to the neural level by using EEG.

The amplitude envelope of speech is one of the critical acoustic properties underlying syllable rate, and is now accepted to be a key component in speech perception, related to speech intelligibility and syllabic parsing (Drullman, 2006). The auditory system is very sensitive to amplitude modulation in natural sounds and encodes amplitude modulation across different frequency channels and at different time scales (Joris et al., 2004). Selectively degrading modulation frequencies near the syllable rate (4–16 Hz) degrades participants' ability to identify consonants and to understand sentences (Drullman et al., 1994). In contrast, speech stimuli that are processed to leave only relatively slow (below 40 Hz) temporal modulations enable near-perfect speech intelligibility (Shannon et al., 1995). When the amplitude envelope is analysed in terms of its constituent temporal modulation frequencies, the dominant modulation frequencies are around 4–6 Hz, reflecting the...
sequential rate of words and syllables (Drullman, 2006). This may indicate that the amplitude rise time deficit found in developmental dyslexia is indicative of impairments in distinguishing the different modulation frequency ranges in speech, particularly the lower frequency modulations (around 4 Hz) associated with syllables (see Goswami, 2011). However, rise time is a complex percept, and the behavioural work in dyslexia to date has used linear envelopes rather than the exponential rise times characteristic of natural speech (see Goswami et al., 2002; Richardson et al., 2004). When linear envelopes are used, sounds with more extended rise times have shorter duration steady-states and also take longer to reach peak intensity. Hence to study the neural response to rise time, it was also deemed important to measure neural responding to intensity and duration in developmental dyslexia.

Few studies to date have examined the effect of rise time on the ERP in humans. Onishi and Davis (1968) found that increasing rise times lead to smaller and slower N1 responses to simple tone stimuli in adults. Similar findings of diminished response amplitude to slower rise times were reported in adults by Skinner and Jones (1968). Overall, subsequent studies with adults (Kodera et al., 1979; Putnam and Roth, 1990; Thomson et al., 2009) corroborated this finding. However, rise-time dependent modulations of ERP components have not been studied in adults with dyslexia. Children’s auditory ERP responses differ considerably from those measured in adulthood (Albrecht et al., 2000; Bishop et al., 2007; Tonnquist-Uitlen et al., 2003; Ponton et al., 2000; Pang and Taylor, 2000). Nevertheless, a little is known about ERP correlates of rise time processing in 8–10-year-old children with dyslexia.

The effects of rise time on basic auditory processing were investigated by Hämäläinen et al. (2008) in 9-year-old children using harmonic tones with linear rise times of either 130 ms (standard) or 10 ms (deviant). Hämäläinen et al. presented tone pairs with an ISI of either 10 ms or 255 ms in an oddball paradigm, in which the longer rise time was always presented first, and the short rise time was occasionally presented as a deviant second tone in the pair. They reported a larger response to the rise time change in the MMN time window in the children with dyslexia only when the ISI between the stimuli was long (255 ms), not when it was short (10 ms). Further, in a previous study using the same stimuli presented with equal probability (Hämäläinen et al., 2007), the Finnish group observed larger P2 responses to the first sound in the pair in control children and a laterality effect of larger responses in the left mastoid channel compared to the right hemisphere in the control children only. The authors interpreted their findings as indicating altered rise time processing in dyslexia.

Close to the age-range considered in our study, Corbera et al. (2006) reported an MMN study of duration processing in 11-year-old children with dyslexia and typically-reading age-matched controls. The standard tone was 100 ms in duration and the infrequent deviant was 33 ms. A significant MMN was found in both groups. However, the MMN amplitude was larger at right and central electrodes in the children with dyslexia, and the MMN was significantly delayed in comparison to the control children. To our knowledge, there are no prior studies of intensity processing in children with dyslexia except by Lovio et al. (2010), where diminished MMN responses to intensity deviants were found in children at risk for dyslexia indicating an auditory processing difficulty.

Measures of rise time, intensity and duration had been used in prior behavioural studies of children with dyslexia, with consistent impairments found for rise time only (Richardson et al., 2004; Thomson and Goswami, 2008; Goswami et al., 2010b). Behavioural thresholds from these prior studies were used to inform the stimulus choices made here. In the current exploratory study, we set out to investigate the possible atypical neural processing of rise time in developmental dyslexia along with neural processing of changes in intensity and duration. To this end, we recorded event-related potentials (ERPs) longitudinally in dyslexic and typically developing children. The neural correlates of duration, intensity and rise time discrimination were explored by recording ERPs in a passive three-stimulus oddball paradigm. To avoid possible effects of attention on ERP components we utilised a passive oddball paradigm where the children did not attend to the tones. We expected an altered MMN response in children with dyslexia as a marker of deficit in rise time discrimination. We also hypothesised that possible sensory deficits will be reflected by altered canonical ERP components therefore general ERP morphology including the P1, N1c, N2 peaks was examined. Furthermore, the cortical reception of tones was studied by presenting the tones used in the oddball paradigm separately in a blocked fashion.

**Methods**

**Participants**

Forty-one children took part in the study, of whom 3 had to be excluded because of insufficient usable EEG data (1 dyslexic, 2 controls). Of the remaining 38, 18 children either had a statement of developmental dyslexia from their local education authority, or showed severe literacy and phonological deficits according to our own test battery. The participants were drawn from a larger cohort of children participating in a longitudinal study of auditory processing in developmental dyslexia (see Goswami et al., 2010b), and comprised all those of similar age and IQ who gave informed consent for EEG. The children were assessed both behaviourally and using EEG over two consecutive years (EEG sessions were 10 months apart on average, S.D. 1.2 m). The 18 children with dyslexia (9 male) had a mean age of 9 years 3 m (S.D. 13 m, range 89–137 months) at the first test point. None of these children had diagnoses of any additional difficulties (e.g. ADHD, dyspraxia, SLI). Twenty of the children (7 male) were chronological age matched controls (mean age 8 years 8 m, S.D. 10.9 m at first test point, range 87–121 months). All of the children had English as a first language and before participating, received a short hearing screen using an audiometer. Sounds were presented in both the left or right ear at a range of frequencies (250, 500, 1000, 2000, 4000 and 8000 Hz), and all subjects were sensitive to sounds within the 20 dB HL range. Parental informed written consent was obtained for all participants. The study received ethical approval from the Cambridge Psychology Research Ethics Committee. Behavioural auditory thresholds for rise time, duration and intensity were collected using a standard psychoacoustic staircase procedure and the protocols described in detail in Goswami et al. (2010b). Further details of the sample, including behavioural auditory thresholds, are presented in Supplemental Table 1.

**Stimuli and procedure**

A pure tone (200-ms duration with 15-ms rise and 15-ms fall times and 75 dB SPL intensity) served as the frequent standard (P = 0.85). In the oddball recording blocks, three rare deviants were presented quasi-randomly in the standard stream (Näätänen et al., 2004; Kujala et al., 2006), each with a probability of 0.05. For each deviant, 180 trials were collected. Deviants differed from the standard either in rise time, intensity or duration. Fig. 1 shows a schematic illustration of the stimuli and the parameters of the four stimuli used are provided in Table 1. All tones had a frequency of 500 Hz. Inter-stimulus interval (ISI) was set to 500 ms. The stimuli were presented binaurally via headphones while the children watched a silent movie. As preliminary analysis of ERP data from year 1 did not yield stable

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Tone parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year 1</td>
</tr>
<tr>
<td>Standard</td>
<td>15 ms 75 dB 200 ms</td>
</tr>
<tr>
<td>Rise-time</td>
<td>90 ms 75 dB 200 ms</td>
</tr>
<tr>
<td>Intensity</td>
<td>15 ms 72 dB 200 ms</td>
</tr>
<tr>
<td>Duration</td>
<td>15 ms 75 dB 160 ms</td>
</tr>
</tbody>
</table>

Parameters of the experimental stimuli.
Mismatch negativity (MMN) responses across conditions, for the second phase of testing (year 2) we increased the physical difference between standard and deviant tones for the intensity and duration conditions. A previous study with adults using the same rise times had been successful (Thomson et al., 2009), and so the rise time deviant was left unchanged. This decision however prevented us from comparing responses to physically different duration and intensity stimuli across the years.

In order to study the simple cortical reception of tones, a Blocked condition was created by presenting 180 trials of each deviant stimulus and of the standard tone in separate blocks. This condition is hereafter referred to as the Blocked condition. In Year 2, the stimuli in the Blocked condition were the new intensity and duration deviants, along with the 90 ms rise time deviant and the standard tone used in both years. Note that as the inter-stimulus interval was kept at 500 ms for all stimuli, this resulted in a slightly faster repetition rate (i.e. shorter SOA) for the shorter duration tones (160 ms in Phase 1 and 140 ms in Phase 2) in the Blocked condition, compared to the repetition rate for the 200 ms long standard, rise time and intensity tones. Presentation of the Blocked condition was counterbalanced across participants (it was given either before or after the oddball stream). Ninety trials of the standard were additionally presented prior to the oddball stream for all participants, to ensure that the standard built up the regularity of repetition prior to the first few trials of the oddball stream.

Discrimination of rise, intensity and duration was designed to be close to normative behavioural thresholds in previous experiments (Richardson et al., 2004; Thomson and Goswami, 2008; Goswami et al., 2010a,b), in order to avoid supra-threshold effects on the MMN which may obscure differences between the groups. As can be seen by comparing Table 1 with Supplemental Table 1, the discriminations chosen were however sub-threshold for normative rise time discrimination for this particular group of participants at test point 1 (control threshold, 95 ms) although not at test point 2 (control threshold, 45 ms), were sub-threshold for normative intensity discrimination at test point 1 (control threshold 4 dB) but not test point 2 (control threshold 4 dB), and were sub-threshold for normative duration discrimination at both test points (control thresholds 92 ms and 87 ms respectively). This was not known at the time of running the ERP study, as some behavioural thresholds were collected after the ERP sessions (due to scheduling imposed by participants’ schools). All deviants were chosen to have lower energy than the standard in order to reduce the influence of ‘fresh’ neural elements in the ERP response.

**EEG recording and data processing**

EEG was recorded using a 65-channel Geodesic Sensor Net referencing to the vertex. Electrode impedances were kept below 40 K Ohm. Data was sampled at 500 Hz, band-pass filtered online at 0.1–200 Hz. Data processing was carried out using the freeware EEGLAB toolbox for Matlab (Delorme and Makeig, 2004). The signals were offline down-sampled at 250 Hz, low-pass filtered at 20 Hz and referenced to the common average. Epochs were extracted from −100 to 600 ms. Trials containing ocular artefacts (monitored at electrodes below, above and next to the eyes), and trials with a potential change below 0.1 μV or voltage exceeding ±120 μV at any of the recording electrodes were rejected from further analysis. Epochs were baseline-corrected for the 100 ms pre-stimulus period and averaged separately for standard and deviant stimuli. The accepted minimum trial number was 50 per condition. All artefact-free standard trials except those immediately following the deviants and all artefact-free deviant trials were used to calculate the mean ERP responses.

Cortical sound discrimination was studied by computing deviant-minus-standard difference waveforms in the Oddball condition. This resulted in a reliable MMN component only for the duration deviants. We report here the deviant-minus-standard comparison from the Oddball condition (Escera et al., 2002; Jemel et al., 2002; Rinne et al., 2005; Schröger and Winkler, 1995).

Cortical sound reception was studied by comparing ERPs between the two groups to the ‘standard’ tone and each ‘deviant’ in the Blocked condition. After averaging, three major components of the evoked brain response were identified visually: a fronto-central P1, a fronto-temporal N1c (also referred to as Tb, cf. Tonquist-Uhlen et al., 2003), and a fronto-central N2 peak (the P1 and N2 showing polarity reversal below the Sylvian fissure), with a time-course and topography (Figs. 4–6) characteristic for this age group (Čepinié et al., 2002; Gomes et al., 2001; Ponton et al., 2000; Sussman et al., 2008). Spatially corresponding electrodes – equivalent to the FCz, FT7, FT8, M1 and M2 positions of the 10–10 system (Nuwer et al., 1998) – were selected for interval and peak latency measurements. Fig. 2 shows schematic topographic headplots of the locations of the five channels selected for plotting and analysis of the MMN (left) and P1-N1c-N2 (right) ERP components. The peak P1, N1c and N2 latencies were identified from the grand-averages waveforms for the standards and deviants at the FCz, M1, M2, FT7 and FT8 sites. Peak latencies were defined as the minimum and maximum points for N1c, P1 and N2 components, respectively. Time windows for latency identification were defined to be sufficiently narrow to measure only the latency of designated peaks. Time windows for amplitude measurements were centered around the grand-averages peak latencies separately for the two hemispheres. Individual mean amplitudes were calculated within the corresponding time intervals. The lengths of time windows were selected to fit the width of the different peaks. Component amplitudes were measured relative to the pre-stimulus period. Time windows defined for amplitude and peak latency measurements are listed in Table 2.

**Statistics**

**Behavioural measures**

The behavioural data were compared using 1-way analyses of variance taking Group as the between-subjects factor. F values and significance levels are shown in Supplementary Table 1.

**Oddball condition — mismatch negativity**

To find intervals where ERPs to standard and deviant tones differed in the Oddball condition, we compared ERPs separately for
each year, group and stimulus-type condition (Standard vs. Rise-time deviant, Standard vs. Intensity deviant, Standard vs. Duration deviant) by point-by-point t-tests (see e.g. Guthrie and Buchwald, 1991). A frontal site (AFz) was selected for further analysis. Mean amplitude data measured within intervals of deviant-minus-standard waveforms, where the difference between standard and deviant responses was marked as significant by point-by-point t-tests, were submitted to independent-samples t-tests separately for data from Phase 1 and Phase 2. Similar t-tests were conducted on MMN peak latency values.

Oddball and Blocked conditions — P1, N1c and N2 components

We compared ERPs recorded in the Oddball condition to tones with slower (90 ms) rise times, tones with lower (72 dB and 68 dB, in Year 1 and Year 2, respectively) intensity and tones of shorter (160 ms and 140 ms, in Year 1 and Year 2, respectively) duration, using ERPs to the standard tone (15 ms rise time, 75 dB intensity, 200 ms duration) as a basis for comparison in each case. ERPs collected in the Blocked condition were analysed in similar ANOVAs, using the blocked presentation of the standard as a basis for comparison. Hence the peak latency and amplitude values of the P1, N1c and N2 components for rise time in the Oddball and Blocked conditions respectively were each submitted to four-way analyses of variance (ANOVAs) with Group (Dyslexic vs. Normal reader) as the between-subjects factor and Rise-time (15 ms vs. 90 ms), Age (Year 1 vs. Year 2) and Hemisphere (Left vs. Right) as repeated-measures factors on data from the Oddball condition and to tones with sharper rise times (15 ms, standard) were analysed and are discussed first. Similar analyses were carried out for the two test phases of the study. The observed significant interactions were further examined by post-hoc Tukey HSD tests. ANOVAs were Greenhouse–Geisser corrected for sphericity violations where necessary. Finally, all analyses involving significant Group effects were re-run as analyses of covariance, using non-verbal I.Q. scores (WISC Blocks) as the covariate. In all cases significant effects were unchanged, hence we report the ANOVAs only below.

Results

Behavioural measures

As shown in Supplementary Table 1, significant differences between groups were found for reading and spelling and for one of the two nonverbal I.Q. sub-tests (WISC Blocks, no significant group differences were found for the two verbal I.Q. sub-tests). The difference in duration discrimination in Phase 2 was significant (p < 0.05), and to rise time it also approached significance (p = 0.054) at Phase 2, both thresholds being higher for the dyslexic group. Otherwise, group behavioural thresholds in the auditory tasks of interest were not significantly different, despite consistently elevated auditory thresholds for the dyslexic group. Nevertheless, neural differences were revealed in the ERPs.

Table 2

Intervals for ERP amplitude and latency measurements.

<table>
<thead>
<tr>
<th></th>
<th>N1c at FT7</th>
<th>N1c at FT8</th>
<th>P1 at Fz</th>
<th>P1 at M1</th>
<th>P1 at M2</th>
<th>N2 at Fz</th>
<th>N2 at M1</th>
<th>N2 at M2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oddball condition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency</td>
<td>160−216</td>
<td>182−216</td>
<td>80−124</td>
<td>80−132</td>
<td>92−120</td>
<td>232−312</td>
<td>228−304</td>
<td>252−292</td>
</tr>
<tr>
<td>Amplitude</td>
<td>172−192</td>
<td>184−204</td>
<td>92−112</td>
<td>100−128</td>
<td>92−120</td>
<td>244−300</td>
<td>240−280</td>
<td>252−292</td>
</tr>
<tr>
<td><strong>Blocked condition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency</td>
<td>160−216</td>
<td>182−216</td>
<td>80−124</td>
<td>80−132</td>
<td>92−120</td>
<td>232−312</td>
<td>228−304</td>
<td>252−292</td>
</tr>
<tr>
<td>Amplitude</td>
<td>172−192</td>
<td>184−204</td>
<td>92−112</td>
<td>100−128</td>
<td>92−120</td>
<td>244−300</td>
<td>240−280</td>
<td>252−292</td>
</tr>
</tbody>
</table>

Time windows in ms selected for N1c, P1 and N2 component amplitude and peak latency measurements.

Oddball condition — mismatch negativity

Point-by-point t-tests (Standard vs. Rise-time deviant, Standard vs. Intensity deviant, Standard vs. Duration deviant) revealed that only Duration deviant tones evoked a reliable differential response with time-course and topography characteristic to the MMN component (Fig. 3). Based on the t-tests, the 292–324 ms post-stimulus interval for data from Phase 1, and the 260–292 ms interval for data from Phase 2 (as measured from tone onset), was selected for statistical analysis of the MMN latency and amplitude. T-tests of the MMN amplitude and latency at the AFz site from the two years of the study did not yield a significant difference between the groups: MMN amplitude in first test phase, (t(36) = 0.42, p = 0.67), latency (t(36) = −0.06, p = 0.95); MMN amplitude in the second test phase, (t(36) = 0.01, p = 0.98), latency (t(36) = 0.6, p = 0.55).

Oddball and Blocked conditions — P1, N1c and N2 components

ERPs waveforms from Phase 1 versus Phase 2 to tones with slower (90 ms, deviant) versus sharper rise times (15 ms, standard) were analysed and are discussed first. Similar analyses were carried out for each test phase for ERP waveforms to tones with higher versus lower intensities (75 dB standard vs. 72 dB deviant for Phase 1, 75 dB standard vs. 68 dB deviant for Phase 2). The analysis of ERP to tones of 90 ms duration provided a significant difference in WMN latency and amplitude. T-tests of the MMN amplitude and latency at the AFz site from the two years of the study did not yield a significant difference between the groups: MMN amplitude in first test phase, (t(36) = 0.42, p = 0.67), latency (t(36) = −0.06, p = 0.95); MMN amplitude in the second test phase, (t(36) = 0.01, p = 0.98), latency (t(36) = 0.6, p = 0.55).
longer and shorter duration was restricted to the P1 response, because the offset response to the shorter tone might have affected the later components. Grand average ERP responses are shown in Figs. 4–6. The mean P1, N1c and N2 amplitude and latency values are detailed in Supplementary Tables 3–9. Results involving differences between the two Groups are given in the text below, results regarding Age, Rise time and Hemisphere factors are detailed in the online supplementary material. A summary of the results of ANOVAs on the latency and amplitude of the fronto-central P1, fronto-temporal N1c, and fronto-central N2 peaks are listed in Supplementary Tables 10–15 for the rise time, intensity and duration analyses in the Oddball and Blocked conditions.

**Results involving significant group differences**

**Rise time**

**Oddball condition**

The ANOVA of the P1 latencies from the FCz site with Group (Dyslexic vs. Control) as the between-subjects factor and Rise-time (15 ms vs. 90 ms) and Age (Year 1 vs. Year 2) as repeated-measures factors yielded a significant main effect of Group (F(1, 36) = 4.1310, p < 0.05). This was caused by slower P1 responses in the Dyslexic group compared to Controls in the Oddball condition. The ANOVA of the P1 amplitudes from the FCz site also yielded a significant Group×Rise time interaction (F(1, 36) = 5.4246, p < 0.05). This was caused by slower P1 responses for the slower rise time stimuli compared to the faster rise time stimuli at the FCz site only in the Dyslexic group (p < 0.05, Tukey HSD), in the Oddball condition. **Blocked condition:** The ANOVA of the P1 latencies at the mastoids yielded a significant Group×Hemisphere interaction (F(1,36) = 6.9487, p < 0.05), caused by faster P1 responses in the right compared to the left hemisphere (p < 0.01, Tukey HSD), observed only in the Dyslexic group, in the Blocked condition. The ANOVA of the N1c amplitudes from the FT7–FT8 sites in the Blocked condition yielded a significant Group×Rise time interaction (F(1,36) = 6.3605, p < 0.05). This was caused by smaller (less negative) N1c responses for the slower rise time stimuli in the Dyslexic group compared to the faster rise time stimuli in the Dyslexic group (p < 0.001, Tukey HSD). The post-hoc test revealed that the fronto-temporal N1c responses for the slower rise time stimuli in the Dyslexic group were also significantly smaller compared to faster rise-time stimuli in the Control group (p < 0.05, Tukey HSD).

**Intensity**

**Oddball condition**

The ANOVA of the P1 latencies from the FCz site with Group (Dyslexic vs. Normal reader) as the between-subjects factor and Intensity (75 dB vs. 72 dB for Phase 1, 75 dB vs. 68 dB for Phase 2) as repeated-measures factor yielded a significant main effect of Group for Phase 1 (F(1, 36) = 4.129, p < 0.05) and also Phase 2 (F(1, 36) = 3.976, p = 0.05). Both effects were caused by slower P1 responses in the Dyslexic group compared to Controls in the Oddball condition. The ANOVA of the P1 amplitudes from the FCz site also yielded a significant Group×Intensity interaction (F(1, 36) = 4.755, p < 0.05) for Phase 2. This was caused by smaller P1 responses for the lower intensity stimuli compared to the higher intensity stimuli at the FCz site only in the Dyslexic group (p = 0.06, Tukey HSD), in the Oddball condition. **Blocked condition:** The ANOVA of the P1 latencies measured at the mastoids in the Blocked condition yielded a significant Group×Hemisphere interaction for test Phase 1 (F(1, 36) = 6.93, p < 0.01) and also Phase 2 (F(1, 36) = 5.234, p < 0.05), caused by faster P1 responses in the right compared to the left hemisphere (p < 0.01 for both phases, Tukey HSD), observed only in the Dyslexic group.

---

**Fig. 4.** Rise time comparisons. ERP waveforms from both test phases of the study, evoked by fast (15 ms, thick lines) and slow rise-time (90 ms, thin lines) tones in the Oddball condition (upper panel) and the Blocked condition (lower panel) for the Dyslexic group (red lines) and the CA control group (black lines).
Fig. 5. Intensity comparisons. ERP waveforms from both test phases of the study, evoked by higher intensity (75 dB, thick lines) and lower intensity (72 dB and 68 dB in test Phases 1 and 2, respectively, thin lines) tones in the Oddball condition (upper panel) and the Blocked condition (lower panel) for the Dyslexic group (red lines) and the CA control group (black lines).

Fig. 6. Duration comparisons. ERP waveforms from both test phases of the study, evoked by standard (200 ms, thick lines) and deviant rise-time (160 ms and 140 ms in test Phases 1 and 2, respectively, thin lines) tones in the Oddball condition (upper panel) and the Blocked condition (lower panel) for the Dyslexic group (red lines) and the CA control group (black lines).
Duration

**Blocked condition**

The ANOVA of the P1 latencies from the FCz site in the Blocked condition with Group (Dyslexic vs. Normal reader) as the between-subjects factor and Duration (200 ms vs. 160 ms for Phase 1, 200 ms vs. 140 ms for Phase 2) as repeated-measures factor yielded a significant Group × Duration interaction for test Phase 2 (F(1, 36) = 4.764, p < 0.005). This was caused by slower P1 responses for the shorter duration stimuli compared to the longer duration stimuli at the FCz site only in the Dyslexic group (p < 0.001, Tukey HSD). ANOVA of the P1 latencies measured at the mastoids yielded a significant Group × Hemisphere interaction for test Phase 1 (F(1, 36) = 6.93, p < 0.05) and also Phase 2 (F(1, 36) = 5.234, p < 0.05), caused by faster P1 responses in the right compared to the left hemisphere, only in the Dyslexic group (p < 0.05 for both phases, Tukey HSD). There were no significant group effects in the Oddball condition.

As noted earlier, analyses of covariance (ANCOVA) were also run on ERP data where significant group effects were found in the analyses of variance (ANOVA), using non-verbal I.Q. scores (WISC Blocks) as the covariate. The ANCOVAs did not change the results and so we report here the results of the ANOVAs only.

**Discussion**

Here we set out to explore the neural response in children with dyslexia to sound rise time, duration and intensity. On the basis of prior behavioural work (Goswami et al., 2002, 2010b; Hämäläinen et al., 2009; Muneaux et al., 2004; Richardson et al., 2004; Surányi et al., 2009), we expected group effects to be strongest for rise time, however this was not the case. Rather, the most conservative explanation of the ERPs is that children with dyslexia have general differences in auditory neural processing in comparison to children of the same age who do not have dyslexia.

The Oddball experiment yielded a reliable MMN to duration only, which was found in both years of testing. The MMN was found for both children with dyslexia and controls, even though in Phase 1 of the study the ERP stimuli used duration differences which were perceptually sub-threshold according to the behavioural data from both groups (the ERP stimuli had a 40 ms duration difference, whereas mean behavioural thresholds were 92 ms for controls and 108 ms for dyslexics). The MMN in Phase 2 was again reliable, here the difference between standard and deviant was 60 ms for the ERP stimuli and group behavioural mean thresholds were 87 ms for controls and 126 ms for dyslexics. The most parsimonious interpretation is that behavioural thresholds are affected by other factors such as distractibility and that neural measures provide a more direct assessment of auditory acuity. On our MMN data, there is no deficit for children with dyslexia in perceiving duration. This result differs from that reported with slightly older children by Corbera et al. (2006). They found a significantly larger duration MMN in the children with dyslexia, with a significant latency difference as well. However, in their study duration was the only deviant parameter, whereas we interleaved duration deviants with rise time and intensity deviants. As the length of the duration deviant was changed from 160 ms in year 1 of the study to 140 ms in year 2, no direct comparison was possible between MMN responses at Phases 1 and 2, even though the standard stimulus remained at 200 ms duration at each test point. Nevertheless, in line with some previous studies (Baldeweg et al., 1999; Huttenen et al., 2007), we found no direct evidence of deficient processing of tone duration in dyslexia.

In contrast to previous studies measuring an MMN response to rise time in children with dyslexia (Hämäläinen et al., 2007; 2008), we found no MMN response to rise time deviants. The discrepancy between previous results and ours may be explained by the considerable differences in the stimuli used. Hämäläinen and his colleagues used 130 ms rise time standards and 10 ms rise time deviants, which is likely to have caused an intensity effect on the evoked brain response (Thomson et al., 2009). Tones with shorter rise times sound louder and presumably recruit fresh neural elements. We used 15 ms rise time standards and 90 ms rise time deviants, and the intensity decrease of the deviants may explain the lack of an intensity effect on the differential response in our study. No reliable MMN response was obtained to intensity deviants in the current study either. This is again discrepant with a prior MMN study (Lovio et al., 2009), however this study utilised a linguistic MMN paradigm based on intensity-deviant syllables and tested 6 year old children. Lovio et al. found an MMN response to occasional ±7 dB intensity variants, and this response was found to be smaller in children at risk for dyslexia (Lovio et al., 2010). In our study, the intensity of the deviants was set to 3 dB or 7 dB lower (no deviant with higher intensity was used in our study) in Phase 1 and Phase 2 of the study, respectively, which may explain the discrepancy between our current and these previous results. Further, the fact that the deviants in our study were below or very close to the children's perceptual thresholds may account for the lack of MMN response to rise time and intensity deviants in our study.

The fronto-central P1-N2 and the fronto-temporal N1c peaks are characteristic components of 8–9 year old children's auditory ERPs (Pang and Taylor, 2000; Ponton et al., 2000; Tonnessaur et al., 2002) and have been suggested to reflect sensory processes (Čeponienė et al., 2002, 2008). The obligatory responses were analysed in both the Oddball and Blocked conditions. Analysis of the Oddball condition for rise time revealed deficient sensory processing in the children with dyslexia, reflected by the longer latency of the P1 response. Analysis of the Oddball condition for intensity yielded similar results, i.e. longer latency of the P1 peak in the children with dyslexia. Furthermore, these group differences were observed in both test phases of the study. A common finding is that P1 latency in children decreases with age and increases with faster repetition rates (Gilley et al., 2005; Sussman et al., 2008; Wunderlich and Cone-Wessons, 2006). As Gilley et al. (2005) point out, developmental changes in myelination, synaptic refinement and cortical fibre density underlie changes in P1 (and other components') latency and amplitude. The authors concluded that in the immature auditory system, incomplete myelination and synaptogenesis will lead to longer neuronal refractory periods and lower cortical excitability. In line with our results, a slower N100m (the magnetic counterpart of the N100 ERP peak, which is the early prominent peak of the adult ERP) evoked by a syllable was observed in adults with dyslexia (Helmeus et al., 2002) and the authors suggested that dyslexia is reflected as abnormal activation of the auditory cortex already 100 msec after speech onset. In 8–12 years old children a longer N250 to syllables showed a slower neural refractory period for children with reading disorders than the control group (Sharma et al., 2007) and the authors conjectured that children with reading disorders have different and slower underlying neural responses than typically developing children. In general, a longer neuronal refractory period in children with dyslexia reflected by a shift in the latency of the P1 response observed in our study, might indicate deficient sensory processing in dyslexia.

The amplitude of the P1 peak showed an effect of rise time and intensity for the children with dyslexia but not for the age-matched controls. The children with dyslexia had a smaller P1 response for the slower rise time stimuli (90 ms rise time) than for the faster rise time stimuli (15 ms rise time), and the P1 response was smaller for children with dyslexia for softer (68 dB) than louder (75 dB) tones in Phase 2. The rise time result is consistent with our previously-published behavioural data (Goswami et al., 2010b), which suggests that children with dyslexia have processing difficulties for more extended rise times (see also Goswami, 2011). Furthermore, a recent study utilising intensity in 6 year old children found smaller P1 responses to standard syllables in the group at risk for dyslexia (Lovio et al., 2010), compared to controls, which also supports the notion that intensity processing is altered in dyslexia. A diminished P1 is most likely to indicate a deficit in sensory processing, as the P1 is unlikely to reflect the operation of a deviance
detection system (like the MMN). The latency of the P1 was similar for fast (15 ms) and slower (90 ms) rise times in controls, and for more/less intense sounds, indicating that the near-threshold difference between standards and rise time/intensity deviants did not cause a measurable difference in the P1 latency of the normal reader group. The smaller amplitude of the P1 response in the children with dyslexia suggests that the neural populations that process slower modulations and/or softer sounds may be immature, smaller or less synchronised in developmental dyslexia. Although the behavioural thresholds for intensity did not differ between the two groups, we found differences in the ERP correlates of stimulus processing. Such discrepant findings are not uncommon in the literature, e.g. Stoodley et al. (2006) reported that auditory event-related potentials differ in dyslexics even when auditory psychophysical performance is normal. These authors argued that dyslexics’ successful coping strategies may positively influence their performance on auditory behavioural measures. An alternative explanation suggested by one of our reviewers is that the P1 amplitude following the energy distribution in the stimuli only in the dyslexic group might indicate that the dyslexic group’s P1 amplitude represents a physical feature (intensity) more accurately than that of the control group. However, the latency of the P1 response was significantly longer for children with dyslexia than for controls. The dyslexia discrimination threshold for rise time was higher in Phase 2 (p = .054) compared to controls and was also higher than controls for intensity. Therefore we suggest that the sensitivity of the P1 amplitude to near-threshold differences might reflect a mechanism compensating for the sensory deficit reflected in the prolonged latency of the P1 peak.

In the Blocked condition we found significant Group × Hemisphere interactions for rise time, duration and intensity comparisons. Analysis of these data revealed a faster P1 response in the right hemisphere than in the left hemisphere for the children with dyslexia only, in all three comparisons, for both phases of the study. As we found no difference in P1 latency between the hemispheres in the control group, the lack of such a laterality effect in the control group suggests that hemispheric differences in the P1 latency are also atypical in dyslexia. The functional significance of faster P1 responses in the right hemisphere is unclear however.

It can be noted that several significant effects observable in the Oddball condition were also present in the Blocked condition, these effects are presented in italics in Supplementary Tables 10–15. Other effects appear to differ for the Oddball and the Blocked conditions. Overall, the relative probability of occurrence of the stimuli was different between the Oddball and Blocked conditions, which might account for differences in the results of the two. Furthermore, analysis of the P1 to the duration stimuli showed slower P1 to the 140 ms long tones compared to the 200 ms tones in the Blocked condition only, for children with dyslexia only. Although the P1 peak is well before the offset of the shorter tone, due to the constant 500 ms ISI used in our study, the repetition rate of the shorter tones (160 ms and 140 ms for Phase 1 and Phase 2, respectively) in the Blocked condition is faster than the repetition of the longer (200 ms) tone. The effect of repetition rate is usually studied by varying the ISI, and in normal-hearing children no difference in P1 latency was found for a syllabic stimulus presented at 360 ms and 560 ms ISI (Giley et al., 2005). We observed no difference in P1 latency for stimuli presented at relatively faster than slower rates in the control group, which is in line with the above results. However, the latency of P1 in children with dyslexia was sensitive to tone repetition rate in the Blocked condition, which suggests that neural refractoriness is atypical in dyslexia. This increase in latency of the P1 for faster repetition rate is in accordance with findings of decreased responsiveness of the P1, reflected by differences in P1 latency and amplitude in rise time and intensity comparisons in the Oddball condition.

Group differences in the amplitude of the N1c component were restricted to rise time processing in the Blocked condition. The N1c is thought to be generated by secondary auditory cortex, most probably the lateral surface of the temporal lobe (Bruneau et al., 1997; Giard et al., 1994; Shahin et al., 2003). The fronto-temporal N1c is the second negative-going subcomponent of the so-called T-complex (Wolpaw and Penny, 1975; Comes et al., 2001), and it has been suggested to originate from a pathway independent from the generators of the adult frontocentral P1-N1b-P2 peaks (Ponton et al., 2000; Tonquist-Uhlen et al., 2003). The N1c was smaller for the slower rise time stimuli (90 ms rise time) than for the faster rise time stimuli (15 ms rise time) for the children with dyslexia only. In addition, the N1c for slower rise time stimuli (90 ms rise time) was smaller for the children with dyslexia compared to the N1c for faster rise time stimuli (15 ms rise time) for the control children. The smaller N1c response for the slower rise time stimuli in the Dyslexic group is consistent with the deficit in the sensory processing and/or sensory representation of slower modulations in speech proposed by Goswami (2011). Also consistent with the current results, significantly smaller temporal N1(c) responses have been reported in 7–10 year old children with dyslexia in a word recognition task (Bonte and Blomert, 2004). The authors interpreted their findings as a speech-specific deficit, however they did not exclude the possibility of a more general deficit in auditory processing. Indeed, deficient pitch (Baldeweg et al., 1999; Kujala et al., 2006) and temporal discrimination (Kujala et al., 2000, 2003) have also been reported in dyslexia (for a recent review on theories of dyslexia, including a general acoustic processing deficit account, see Schulte-Körne and Brüder, 2010). Recent results from a multi-feature paradigm in 6 year old children (Lovio et al., 2010) suggest wide-spread auditory deficits in children at risk for dyslexia.

Several maturational effects of ERP components were also observable in our rise time data, including a decrease in P1 latency, both in the Oddball and the Blocked condition, which is in agreement with prior results (Sussman et al., 2008). A P1 amplitude decrease with increasing age was also observed, together with an N1c amplitude decrease with increasing age, in line with previous reports (Comes et al., 2001; Pang and Taylor, 2000; Ponton et al., 2000). These effects reflect developmental changes over the time period separating the first and second EEG recording in our study (approximately one year). Several rise time and laterality effects were found in the rise time comparisons, which were highly consistent across the Oddball and Blocked conditions. Larger and faster P1 responses were found for faster compared to slower rise time stimuli. This is consistent with previous reports that an increase in rise time evokes smaller P1 amplitudes and longer peak latencies (Kodera et al., 1979), furthermore the phase-locking of several sub-bands of the ERP response was found to be sensitive to rise time characteristics in a corresponding manner (Shahin et al., 2010). Larger (more negative) N1c and N2 responses with shorter latencies were observed in our study to faster compared to slower rise time stimuli. Prior studies in 8–10 year old children (Hämäläinen et al., 2007) and adults (Putnam and Roth, 1990; Onishi and Davis, 1968; Thomson et al., 2009) reported concordant effects of rise time on temporal N1a and fronto-central N1b, however we found no studies in the literature investigating the effect of rise-time on N1c and N2. Significant laterality effects were found in our study for all three components investigated, consistently for the Oddball and Blocked conditions. More robust P1 responses were observed in the left hemisphere with shorter latencies in the right hemisphere, which is in agreement with previous results to tone stimuli in adults (Ross et al., 2009), whereas the latency of the N1c and N2 peaks was shorter in the left hemisphere.

Several amplitude and laterality effects were also found in the intensity comparisons, and the laterality effects were highly consistent across the Oddball and Blocked conditions. Intensity effects included faster P1 and N1c responses to the louder compared to the softer tones and larger P1, N1c and N2 responses to the louder compared to the softer tones in the Blocked condition. This is in line with previous findings of shorter ERP peak latencies to higher intensity tones (Bruneau et al., 1997; Dinces and Sussman, 2008). The P1 and N2 responses were faster at the right, compared to the left mastoid, whereas the N1c peak
was faster at the left, compared to the right fronto-temporal electrode. A faster P1 response was observed at the right, compared to the left mastoid for duration stimuli in the Oddball and Blocked conditions. The laterality effects showed a high consistency across the different stimulus comparisons and main experimental conditions.

In summary, the data we report here are consistent with impaired auditory neural processing mechanisms in children with reading difficulties, but are not clear with respect to whether one auditory parameter is more impaired than others. The data are most consistent with the view that children with dyslexia show general auditory impairments. This makes it premature to speculate about educational interventions. Nevertheless, the consistency with which auditory difficulties are reported in the dyslexia literature suggests that a focus on oral language is critical for an effective reading curriculum. Although learning to read is sometimes considered a visual task, reading is parasitic on the spoken language system, and the data reported here suggest that clear instruction in the acoustic similarities and differences between spoken words is likely to be a useful aspect of reading instruction.

Acknowledgments

We thank Prof. István Winkler for his invaluable comments on data analysis. We also thank the participating children, their families and their schools for their help and support. This research was supported by the Medical Research Council, Ref. G0400574, and an EU Framework VI STREP grant, Humans as Analogy Makers. Usha Goswami is also supported by a Major Research Fellowship from the Leverhulme Trust. Requests for reprints should be addressed to Usha Goswami, Centre for Neuroscience in Education, Downing St., Cambridge CB2 3 EB, UK.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.neuroimage.2011.04.005.

References


