Auditory processing in the dyslexic brain

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Abstract

A prominent theory of dyslexia states that it is caused, at least in part, by neural deficits in processing auditory information. We examined children with dyslexia for their brain responses to sounds which were designed to challenge the temporal processing capabilities of the auditory system. The sounds were 500-ms broadband noises containing a binaurally embedded pitch. Event-related brain responses were measured with simultaneous 64-channel electroencephalography (EEG) and 160-channel magnetoencephalography (MEG). Nine children with dyslexia and 9 age-matched controls were tested (2 females in each group, Mean age 9.5). During the brain measurements children viewed a video and ignored the acoustic stimuli. Children tolerated the experimental environment well and we were able to collect data from all subjects for 800 trials over a 40-minute experimental session. This resulted in auditory responses with a high signal-to-noise ratio, important because children's auditory responses tend to be considerably noisier and more variable than those of adults. Results showed a delayed neural response to binaural pitches in children with dyslexia compared to control children.

Keywords: Auditory processing; dyslexia; neuroimaging; dichotic pitch.

Introduction

Developmental dyslexia is an unexplained difficulty in learning to read that is thought to affect 5-10 percent of school age children. This difficulty occurs despite adequate education and normal intelligence (Habib, 2000). There is evidence that dyslexia is associated with problems in processing the phonological features of words (Bradley and Bryant, 1983). In addition to linguistically-based deficits, a number of researchers have reported deficits in non-linguistic brain processes, including low-level problems in auditory sensory processing. The nature of these auditory deficits, and how they might contribute to the phonological processing deficits in dyslexia and other linguistic disorders, such as specific language impairment (SLI), remain unclear and are strongly debated. A number of current hypotheses hold that auditory processing deficits are rooted in problems in processing crucial kinds of timing information contained in speech and non-speech sounds.

The 'temporal processing deficit' hypothesis proposes that individuals with dyslexia have a general difficulty in processing stimuli that change rapidly over time. This could impair the acquisition of phonology which is presumed to subserve reading acquisition (Habib, 2000). This hypothesis also states that a deficiency in the cognitive areas specific to temporal coding may be the cause of more complex cognitive dysfunctions observed in dyslexics such as a lack of awareness of time passing and difficulties processing the sequence of successive events (Habib, 2000).

Problems in processing the fine temporal structure of sounds have also been used to explain evidence for deficits in binaural auditory processing in dyslexia. Timing differences between sounds arriving at the two ears are termed “interaural timing differences” (ITDs) and arise due to the time it takes for sound to transit between the ear closer to a sound source and the ear further from the sound source. In normal hearing, we rely on these small (several hundred microseconds) ITDs to separate...
sounds from background noises and to locate them in auditory space. A number of psychophysical studies have reported impaired processing of binaural timing information in dyslexia (McAnally and Stein, 1976; Dougherty et al., 1998; Edwards, Giaschi and Dougherty, 2004), although others have found no differences between dyslexics and controls in their binaural processing capabilities (Amitay, Ahissar and Nelken, 2002; Hill, Bailey, Griffiths and Snowling, 1998).

In a recent investigation, Chait et al. (2007) measured detection thresholds for dichotic pitch, a sound that requires binaural processing to produce a perception of a separate pitch in background noise. These investigators found no difference in dichotic pitch thresholds between a group of adults with developmental dyslexia and a group of normal reading control subjects. However, they did find that the adults with dyslexia were less able to detect pitches in background noises, irrespective of binaural processing. This was manifested by response times that were 120 ms slower in the dyslexics.

We present preliminary results of a study designed to elucidate the stage(s) of cortical processing, measured by electroencephalography (EEG) and magnetoencephalography (MEG), that may be responsible for delayed detection of sounds in background noises in dyslexic subjects observed by Chait et al. (2007) using a dichotic pitch stimulus similar to the one used by that group.

### Method

This project was approved by the Macquarie University Human Participants Ethics Committee.

### Subjects

Data were recorded from nine children with dyslexia and nine age-matched control children (See Table 1). All children had normal hearing, had non-verbal IQ (NVIQ) scores in the average range, and all bar one reported being right handed. The children with dyslexia, as a group, had significantly poorer nonword reading, irregular-word reading, and receptive and expressive phonology than the controls (see Procedure for tests). They also had significantly lower NVIQ scores, but this was a function of the unusually superior NVIQ of the controls. The mean NVIQ scores of the children with dyslexia was very close to average.

<table>
<thead>
<tr>
<th>Table 1. Subject characteristics within each group.</th>
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<tr>
<td><strong>Control</strong></td>
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<td>n</td>
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<tr>
<td>Age</td>
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<tr>
<td>Nonverbal IQ</td>
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<tr>
<td>Irregular-word reading</td>
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<tr>
<td>Non-word reading</td>
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<tr>
<td>Receptive and expressive phonology</td>
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</table>

### Stimuli

Two kinds of acoustic stimuli were employed. Control stimuli consisted of identical 500-ms broadband Gaussian noises (sampling rate, 44.1 kHz) presented to the two ears. This stimulus results in a perception of a ball of noise located in the centre of the head. Dichotic pitch stimuli (hereafter referred to as pitch stimuli) were produced by introducing a 500 µs interaural lag to a narrow band (600-800 Hz) of frequencies. This stimulus results in the perception of two concurrent sounds: the ball of noise in the centre of the head, and a circa 700 Hz “pitch” lateralized to the side of the temporally-leading ear.

The stimuli were designed digitally using LabView software (Version 8.6, National Instruments, Austin, TX) generated on two channels of a 16-bit converter (Model NI USB 6251, National Instruments, Austin TX). The
level of the sounds was adjusted using programmable attenuators (model PA4, Tucker Davis Technologies, Alachua, FL) to yield 70 dB SPL at the eardrum. Stimuli were delivered to listeners using insert earphones (Etymotic Research Inc. Model ER-30, Elk Grove Village, IL). Stimuli were presented binaurally with a random interstimulus interval between 800 and 1200 ms.

**EEG/MEG Measurements**

Prior to EEG and MEG measurements, EEG electrode caps and MEG marker coils were placed on a subject’s head. Marker coil positions, electrode positions and head shape were measured with a pen digitizer (Polhemus Fastrack, Cochester, VT). All measurements were carried out with subjects lying down in the MEG machine. EEG and MEG setup was well tolerated by all subjects. MEG recordings were obtained in a magnetically shielded room using the KIT-Macquarie MEG160 (KIT, Kanazawa, Japan) system, which consists of 160 coaxial first-order gradiometers with a 50 mm baseline. MEG data were sampled at a rate of 1000 Hz and bandpass filtered from 0.03-200 Hz. EEG data was recorded using a Brainproducts 64 channel EEG using the same sample rate and filter bandpass. EEG results are not described in the present report.

**Analysis**

MEG data were analysed off-line using BESA version 5.2.4 (MEGIS Software GMBH, Grafelfing, Germany). MEG data were segmented and averaged into 500-ms epochs including a pre stimulus baseline of 100-ms. Averaged data were filtered with a bandpass of 0.16-30 Hz.

Source analysis was carried out by modeling the MEG data with two symmetric dipole sources in a spherical volume conductor fitted to the digitised surface of the head.

Statistical analyses focused on the main component of the surface waveform, the p100m component (80-150 ms). Surface waveforms were summarized by computing the root mean square (RMS) of the 20 sensors with the largest amplitude M100 responses (10 for each hemisphere). Component latencies were computed using an automated peak finding utility in BESA 5.2.

**Procedure**

A battery of cognitive tests were administered to both control and dyslexic subjects prior to EEG/MEG setup. Nonverbal IQ (NVIQ) was measured with the Matrices subtest of the KBIT 2. Irregular-word reading and nonword reading was measured with the Castles and Coltheart 2. Receptive and expressive phonology was measured with the nonword repetition subtest of the NEPSY-II. Handedness was indexed with the Oldfield Handedness Questionnaire (See Table 1). Auditory thresholds were checked using an Otovation Amplitude T3 series audiometer (King of Prussia, PA). Subjects with pure-tone thresholds greater than 15 dB HL were excluded.

During the EEG/MEG recordings, children ignored the experimental stimuli while viewing a movie of their choice, played with low-level video sound. Previous ERP research has shown that viewing a video during electrophysiological recordings increases compliance with little impact on the reliability of electrophysiological responses (McArthur, Bishop and Proudfoot, 2003). Four 10-minute blocks of randomly interleaved control and pitch stimuli were presented. Each block contained 216 stimuli, for a total of 432 stimuli of each type. Stimulus blocks were presented consecutively with a short break in between during which marker coil measurements were obtained.

**Results**

Both types of acoustic stimuli elicited event-related magnetic fields (ERFs) characterized by a large amplitude peak at a latency of about 100 ms, termed the p100m component. In both groups of subjects, this component showed an anterior-posterior pattern of flux reversal over bilateral temporal lobes, consistent with dipolar sources located within the depths of the Sylvian fissure. Dipole source analysis confirmed that the sources of the p100m component were well-modelled with bilateral sources centred in Heschl’s gyri on the superior surface of the temporal lobes (Figure 1).

![Fig. 1. Source model for p100m data from a representative subject showing sources centred in bilateral auditory cortices.](image)

The p100m response, showed a significantly longer latency for the dylexic group compared to the control group in both hemispheres. For the left hemisphere, the mean latency difference between groups was 15 ms (p < .05), while for the right hemisphere the mean delay was 14 ms (p < .05). No significant group differences were found for the control stimuli. Latencies of P100m responses to the pitch stimuli for left and right hemispheres are summarized in Table 2.
Table 2. Latencies of P100m responses for the dichotic pitch stimulus.

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<tr>
<th></th>
<th>Left Hemisphere</th>
<th>Right Hemisphere</th>
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<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Dyslexic</td>
</tr>
<tr>
<td>121</td>
<td>131</td>
<td>112</td>
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<td>113</td>
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<td>119</td>
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<td>106</td>
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<td>107</td>
</tr>
<tr>
<td>Mean</td>
<td>116.7</td>
<td>131.9</td>
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<tr>
<td>StDev</td>
<td>14.3</td>
<td>15.2</td>
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</table>

Conclusions

The present study compared the brain responses of children with and without dyslexia to dichotic pitch stimuli that taxed the temporal processing capabilities of the auditory system. These stimuli contained binaural timing information that elicits a perception of a separate pitch embedded in noise. The preliminary MEG results presented here indicate that children with dyslexia have a delayed neural response to pitch stimuli relative to control children. This p100m response was significantly delayed in both cerebral hemispheres.

A previous psychophysical study (Chait et al., 2007) reported that dyslexic adults showed significantly slower reaction times (RTs) in a task in which they were required to identify a tone in background noise. Our results confirm that part of the RT delay can be attributed to delays in neural processing in the auditory system.

Our finding of delayed P100m responses to dichotic pitch stimuli in children with dyslexia also support the findings of Sebastian and Yasin (2008) who identified a deficit in processing binaural tone stimuli in dyslexic subjects but not in processing diotic or monotic stimuli. The delayed P100m responses in both cerebral hemispheres supports previous findings that children with dyslexia have atypical brain responses to sounds in both hemispheres when compared to controls (Abrams et al., 2009; Heim, Eulitz and Elbert, 2003; Paul et al., 2006).

Our source analyses of these preliminary data indicated the p100m response originated in bilateral auditory cortex. Although further analysis is needed in order to assess differences in source locations between dyslexic and control subjects, these preliminary findings point to a difference in cortical organisation in dyslexic subjects as far as the processing of auditory information is concerned. The difference seems to relate to the mechanisms involved with the processing of binaural information. Whether or not this difference is the initial stages of processing at the brain stem, or is specific to higher-level structures (Johnson, Hautus and Clapp, 2003) is yet to be established. Since binaural unmasking is thought to play an important role in enabling listeners to detect objects in noisy environments (Chait et al., 2007), it follows that a child with dyslexia may struggle to hear a teacher in a noisy classroom. This may lead to difficulties in learning the syllables and phonology (Helenius et al., 2009) of new words. Further analysis of the findings in the current study will contribute to a greater insight into the causes of developmental dyslexia and subsequently its treatment.

In summary, we found that children tolerated the MEG environment well, and we were able to collect data from all subjects for 800 trials over a 40 minute experimental session. This resulted in auditory evoked responses with a high signal-to-noise ratio, important because children’s auditory responses tend to be considerably noisier and more variable than those of adults. Our preliminary analyses of the MEG data show a significantly delayed neural response to the dichotic pitch stimuli in children with dyslexia relative to control children. These findings support the interpretation that one of the neurological bases of dyslexia may be a deficit in processing timing information contained in sounds. In future work we will carry out a more comprehensive analyses of these hemispheric differences and the brain sources of these responses, and we will examine the relationship between concurrent EEG and MEG measurements of brain function to determine if these measurements provide...
redundant or complementary information about brain functioning in dyslexia.

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