Neuropsychologia 51 (2013) 633–641

Contents lists available at SciVerse ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Lateralized auditory brain function in children with normal reading ability and in children with dyslexia

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ARTICLE INFO

Article history:
Received 24 April 2012
Received in revised form
8 December 2012
Accepted 17 December 2012
Available online 17 January 2013

Keywords:
Auditory cortex
Auditory evoked potentials
Dyslexia
Electroencephalography
Magnetoencephalography
Reading acquisition

ABSTRACT

We examined central auditory processing in typically- and atypically-developing readers. Concurrent EEG and MEG brain measurements were obtained from a group of 16 children with dyslexia aged 8–12 years, and a group of 16 age-matched children with normal reading ability. Auditory responses were elicited using 500 ms duration broadband noise. These responses were strongly lateralized in control children. Children with dyslexia showed significantly less lateralisation of auditory cortical functioning, and a different pattern of development of auditory lateralization with age. These results provide further evidence that the core neurophysiological deficit of dyslexia is a problem in the balance of auditory function between the two hemispheres.

1. Introduction

Developmental dyslexia is an unexplained difficulty in learning to read, despite adequate education and normal intelligence (Habib, 2000). It is thought to affect 5–10 per cent of school-aged children. The underlying causes remain unknown, but much current research focuses on explanations involving auditory processing problems, and/or abnormalities in hemispheric lateralisation of brain function.

Auditory processing explanations of dyslexia have been the subject of considerable interest and debate (e.g. Bishop, 2006; McArthur & Bishop, 2001; Ramus, 2006; Temple, 2002). In general, these explanations hold that reading problems stem from difficulties in processing and representing certain auditory features, which degrades the ability of the brain to accurately sample crucial elements in the speech stream (Goswami, 2011; Hari & Renvall, 2001; Tallal, 2004). These difficulties impair a child's ability to pair speech sounds with letters, which is a basic skill required for learning to read new words.

Theorists have long speculated that the biological basis of dyslexia is an imbalance of activity of the two hemispheres (Orton, 1925). Indeed this position has been supported by anatomical (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985), structural (Larsen, Hoien, Lundberg, & Odegaard, 1990; Leonard & Eckert, 2008), and functional neuroimaging (Illingworth & Bishop, 2009; Shaywitz et al., 1998) findings of atypical cerebral lateralization in dyslexic adults and children. Recent theoretical models of speech perception emphasise the importance of an asymmetric routing of different kinds of acoustic information to the two hemispheres (Poeppel, 2003; Zatorre, Evans, Meyer, & Gjedde, 1992) and current theories of dyslexia suggest that the maturation of phonological processing abilities is dependent on the appropriate development of information processing biases in the two hemispheres (Abrams, Nicol, Zecker, & Kraus, 2009; Goswami, 2011; Tallal, 2004). Others have suggested that altered patterns of auditory lateralization might be responsible for both pathological (e.g. dyslexia and schizophrenia) and supranormal (e.g. absolute pitch) cognitive function (Tervaniemi & Hugdahl, 2003).

Several recent magnetocencephalography (MEG) studies have reported reduced hemispheric asymmetry of auditory function in dyslexia using dipole source locations as a basis for an asymmetry index (Edgar et al., 2006; Heim, Eulitz, & Elbert, 2003; Paul, Bott, Heim, Eulitz, & Elbert, 2006). Heim et al. (2003) computed dipole source locations for the P100m response to a synthetic German syllable [ba:] and found a more symmetric source configuration in

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http://dx.doi.org/10.1016/j.neuropsychologia.2012.12.015

children with dyslexia compared to control children aged 8–15 years, while Edgar et al. (2006) reported a similar result for location of M100 sources of responses to non-linguistic stimuli in dyslexic and schizophrenic adults. Paul et al. (2006) attempted to replicate the results of Edgar et al. (2006) in a large sample of 64 dyslexic children aged 8–10 years. While these authors were unable to obtain reliable source locations for the P100m component, source locations for the later N260m component showed reduced asymmetry in the dyslexic children.

The reliability of dipole source locations is a significant problem for data from individual children, primarily because the accuracy of source modelling is critically dependent on the signal-to-noise ratio (SNR) of the event-related magnetic fields (ERFs) measured with MEG and event-related potentials (ERPs) measured with EEG. This SNR is typically much lower in children's ERFs and ERPs than in data obtained from adults (Luck, 2005; Pang, 2011). In practice this problem is more severe and intractable with MEG data: ERPs can be readily averaged across subjects to improve the SNR, while ERFs cannot. This is largely because EEG electrodes are placed in fixed anatomical positions on the head, while the MEG sensors are not.

In the present study we aimed to avoid this problem using an auditory lateralisation metric based on the amplitude of dipoles with fixed positions, in a paradigm that placed minimal demands on children's vigilance and attention to experimental stimuli. This lateralisation index provides a robust and reliable measure of functional brain asymmetry in typically developing children; and is a sensitive index of atypical auditory lateralisation in the brains of children with dyslexia.

2. Method

2.1. Subjects

Data were recorded from 16 children with dyslexia and 16 age-matched control children. Written consent was received from the parents of all children and all procedures were approved by the Macquarie University Human Participants Ethics Committee. Children were recruited from schools, clinics, and via newspaper advertisements. All children were aged from 7 to 12, had no history of neurological or sensory impairment as indicated on the background questionnaire (see test battery below) and spoke English as their first language at school and at home. The children with dyslexia scored at least 1 SD below the age-mean on the Castles and Coltheart 2 (CC2; Castles et al., 2009) non-word reading test or irregular word reading test (see test battery below). The control children scored within 1 SD of the age-mean on the CC2 non-word reading test and the irregular word reading test.

Children were assessed using a test battery designed to measure non-verbal IQ (NVIQ), reading proficiency, and phonological awareness. These tests included the Matrices Non-verbal subtest of the KBIT 2 (Kaufman & Kaufman, 2004), the Non-word repetition subtest of the NEPSY-II (Korkman, Kirk, & Kemp, 1998) and the Castles and Coltheart 2 (Castles et al., 2009). The Castles and Coltheart 2 has subtests that measure regular, irregular and non-word reading. Handedness was assessed with the Oldfield Handedness Questionnaire (Oldfield, 1971). Auditory thresholds were checked using an Otovation Amplitude T3 series audiometer (Otovation LLC, King of Prussia, PA). Subjects with pure-tone averages greater than 15 dB HL were excluded from the electrophysiological recordings.

Table 1 summarises the demographic and test results for the two groups. The two groups did not differ significantly in age, sex, or handedness. Nor did they differ on a non-word repetition task—a measure that is known to be particularly sensitive to spoken language impairment. As expected, the two groups did differ on measures of reading accuracy for non-words, irregular words, and regular words.

The two groups also differed on the measure of non-verbal IQ. The children with dyslexia, on average, performed close to the level expected for their age, while the controls, on average, performed above the average range. The participants also showed a wide range of scores on non-verbal IQ, with four dyslexic participants and two controls scoring more than 1 SD below their group means. On this issue we note that in recent years, there is growing evidence (and hence increasing acceptance) that intelligence is not a predictor of reading ability, and is not a predictor of response to reading intervention (see Gresham & Vellutino, 2010; Hulme & Snowling, 2009). Thus, IQ is rapidly being abandoned as a criterion for inclusion/exclusion into groups with dyslexia. Where relevant we have also partialled out the effect of IQ in statistical analyses to confirm that this variable did not play a role in our analyses.

2.2. Stimuli

Stimuli were 500 ms duration broadband noises of two kinds: *Noise only* stimuli, which result in a perception of a noise located in the centre of the head, and *Dichotic Pitch* (DP) stimuli, which were monaurally identical to the noise only stimuli but contained an interaural time shift for a narrow frequency band (Hautus & Johnson, 2005; Johnson, Hautus, & Clapp, 2003) resulting in the perception of a central noise and a lateralised pitch. The dichotic pitch stimuli were included to assess the possibility of binaural hearing deficits in the children with dyslexia (Dougherty, Cynader, Bjornson, Edgell, & Giaschi, 1998).

To produce the stimuli, we generated two independent broadband Gaussian noises of 500 ms duration at a sampling rate of 44,100 Hz. One noise was bandpass filtered (4th order Butterworth) with a centre frequency of 600 Hz and a half-power bandwidth of 50 Hz. The other noise was notch filtered using the same corner frequencies as the bandpass filter. The notch filter was designed so that the sum of the filter functions for the notch and bandpass filter was equal to one for all frequencies. Consequently, for these complementary filters, the sum of the two waveforms is a noise process with a flat spectrum (Dougherty et al., 1998). The bandpass filtered noise was duplicated and, to produce the DP stimuli, one copy was temporally delayed by 0.5 ms. For the noise only stimuli, no delay was introduced. The notch filtered noise was then added to each copy of the bandpass filtered noise, producing two spectrally identical noises. The bandwidth of the two spectrally-flat noises was determined by a bandpass 4th order Butterworth filter with corner frequencies 400 and 800 Hz. All stimuli were windowed with a Hanning ($\cos^2$) function with 10 ms rise and fall times. For the DP stimuli, the noise process with the temporally advanced narrow-band of frequencies was presented to the right ear of the listener and the other noise was presented to their left ear, leading to a perception of a right-lateralized pitch.

Stimuli were designed digitally using LabView software (Version 8.6, National Instruments, Austin, TX) and generated on two channels of a 16-bit D-A 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 (Model ER-30, Etymotic Research Inc., Elk Grove Village, IL) with a random interstimulus interval (ISI) between 800 and 1200 ms, chosen because ISI's shorter than these are known to suppress some components of the auditory evoked response in younger children (Čeponienė, Cheour, & Näätänen, 1998; Gilley, Sharma, Dorman, & Martin, 2005; Sussman, 2008) due to developmental changes in refractoriness.

2.3. MEG and EEG acquisition

Prior to EEG and MEG measurements, EEG electrode caps and MEG marker coils were placed on the subject's head. Marker coil positions, electrode positions, and head shape were measured with a pen digitizer (Polhemus Fastrack, Colchester, VT). All measurements were carried out with the subject in a supine position in the MEG environment. MEG recordings were obtained in a magnetically shielded room (Fujihara Co. Ltd., Tokyo, Japan) using the KIT-Macquarie MEG160 (Model PQ1160R-N2, KIT, Kanazawa, Japan) consisting of 160 coaxial first-order gradiometers with a 50 mm baseline (Kado et al., 1999; Uehara et al., 2003). EEG was recorded using a 64-channel BrainAmp MR plus MEG-compatible EEG system (BrainProducts GmbH, Gilching, Germany). EEG electrodes were Ag/AgCl in a BrainCap MR electrode cap, consisting of 62 channels of EEG, 1 channel of EKG, and 1 channel of EOG, all referenced to Cz. Both MEG and EEG data were acquired using a sampling rate of 1000 Hz and a filter bandpass of 0.03–200 Hz.

2.4. Procedure

Hearing and cognitive tests were administered to participants prior to EEG/MEG setup. During the EEG/MEG recordings, children were permitted to ignore the experimental stimuli while viewing a movie of their choice, played with low-level video sound (McArthur, Bishop, & Proudfoot, 2003). The movie was projected via a data projector on to a screen located 120 cm above the participant's head. The projection subtended a visual angle of 12.3° (vertical) $\times$ 21.2° (horizontal), providing a comfortable viewing experience requiring few or no eye movements. Prior to the start of the experiment, participants were instructed to remain as still as possible during the recording session and to minimise eye movements and eyeblinks. Eye and head movements were continuously monitored via a closed circuit camera. When excessive movements were detected the experiment was paused and the movement instructions were re-issued to the participant. Four 10-min blocks of randomly interleaved noise only and DP stimuli were presented. Each block contained 216 stimuli, for a total of 432 of each of noise only and DP stimuli (864 trials in total). Stimulus blocks were presented consecutively with a short interval in between during which head position was measured. The head movement tolerance threshold was < 5 mm for any marker coil from start to end of the recording session.