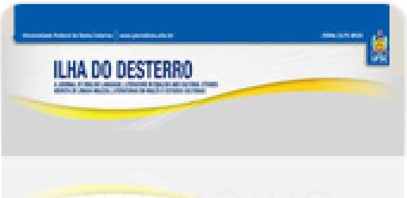

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LEXICAL DECISION MAKING IN ADULTS WITH DYSLEXIA: AN EVENT-RELATED POTENTIAL STUDY

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Abstract

Performance on a lexical decision task was investigated in 12 English speaking adults with dyslexia. Two age-matched comparison groups of unimpaired readers were included: 14 monolingual adults and 15 late proficient bilinguals. The aim of the study was to determine the timing of neural events with event-related potentials (ERPs) during lexical decision-making between individuals with dyslexia and unimpaired readers (both unilingual and bilingual). ERPs were calculated for posterior sites in the left and right hemispheres and the P1 and N170 components were compared between groups. Event-related EEG coherence (measuring the synchrony of neural events during lexical tasks both between and within cerebral hemispheres) was also calculated for seven electrode pairs (three pairs at symmetrical locations between hemispheres, and two pairs within each hemisphere). We chose to recruit two comparison groups of unimpaired readers to better clarify the findings resulting from the right hemisphere (EEG) coherence analysis. That is, both late-proficient bilinguals and adults with dyslexia are thought to rely on right hemisphere resources during reading. We hypothesized that those with dyslexia would show less within-hemisphere coherence and more between-hemisphere coherence than bilingual individuals. Dyslexics had both lower amplitude and longer latency N170 activation than unimpaired readers, suggesting asynchronous neural activity. Dyslexics showed greater synchrony between hemispheres in gamma range frequencies whereas the bilingual group showed greater synchrony in the theta frequency band (both within and between hemispheres). This study demonstrates that individuals with developmental dyslexia have reduced amplitudes in the N170 and higher synchrony between hemispheres during a reading task. The differences may be due to an asynchrony of neuronal activity at the point where word form features are distinguished.

Keywords: Developmental Dyslexia, English, bilingual, electrophysiology, oscillation, theta, gamma, coherence, EEG, ERP, reading, cerebral laterality.

Reading draws on a variety of brain functions in order to link symbols to words and concepts (Shaywitz & Shaywitz, 2008). Some children have great difficulty attaining this vital skill and, if it persists, may have a specific reading disability (herein called dyslexia). Dyslexia is a persistent and unexplained failure to achieve accurate and/or fluent word recognition skills, despite adequate intelligence and opportunity (Lyon, Shaywitz, & Shaywitz, 2003). While many adults who have reading difficulties in childhood are eventually able to read accurately, their reading often remains slow and effortful with persistent spelling and written expression deficits (Habib, 2000).

The primary cognitive deficit in dyslexia can be traced back to deficient phonological coding, which impairs the way that speech sounds are represented, stored and retrieved (Shaywitz & Shaywitz, 2005). Indeed, a disruption in the ability to link graphemes and phonemes has been evidenced by anatomical (e.g., Galaburda & Kemper, 1979; Galaburda, Rosen, & Sherman, 1990; Pernet, Andersson, Paulescu, & Demonet, 2009; Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010; Steinbrink et al., 2008; Temple, 2002) and functional (Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; Shaywitz et al., 2002; Shaywitz, Mody, & Shaywitz, 2006; Shaywitz & Shaywitz, 2008) studies.

There are also clear electrophysiological changes during processing of written words in those with dyslexia (Breznitz, Shaul, & Gordon, 2003; Csepe, Szucs, & Honbolygo, 2003). For example, the Event-related Potential (ERP) N170 component, occurring over occipital and temporal areas at 150-200ms and sensitive to word form (Nobre, Truett & McCarthy, 1994), has been found to be reduced and slower in both the auditory (review by Lyytinen, Guttorm, Huttunen, Hamamainen, Leppanen, & Vesterinen, 2005) and visual (Breznitz, Shaul, & Gordon, 2003; Kast, Elmer, Jancke, & Meyer, 2010) domains in those with dyslexia compared to unimpaired readers. According to Lyytinen, et al. (2005), findings are consistent with reduced metabolic activation of left posterior regions.

With electrophysiological data, in addition to ERP amplitude and latency differences, EEG coherence (synchrony) can be calculated to measure inter- and intra-hemispheric processing. Here communication between areas subserving reading can be examined by investigating the similarities in the electrical frequency spectrum between two EEG electrodes. This is thought to relate to the shared functional integrity of the two areas (Broman, Rudel, Helfgott, & Kriegler, 1985). In the field of dyslexia, there is a paucity of data with this measure, despite growing acceptance that connectivity between reading areas may be functionally disrupted in these individuals (Pugh, Mencl, Jenner, Katz, Frost, Lee, et al., 2001; Waldie, 2002).

In earlier coherence studies, children with dyslexia had lower interhemispheric synchrony in the theta band during reading tasks than unimpaired readers (Leisman, 2002; Leisman & Ashkenazi, 1980; Sklar, Hanley, & Simmons, 1972). Higher alpha and lower beta band interhemispheric coherence have also been demonstrated in Japanese children compared to unimpaired readers during reading tasks (Shiota, Koeda, & Takeshita, 2000). Shiota et al (2000) also found higher alpha band coherence within the right hemisphere in dyslexic children. No differences between hemispheres were found between children with comorbid dyslexia and Attention Deficit Hyperactivity Disorder disability compared to those with single impairments (Barry, Clarke, McCarthy, & Selikowitz, 2009). However, children with dyslexia exhibited reduced synchrony in the beta and delta frequencies and higher in alpha within the left hemisphere.

It is unknown whether adults with dyslexia show differences in functional connectivity during reading tasks, either within and/or between hemispheres, compared to unimpaired readers. If adults with dyslexia utilise right hemisphere resources as compensation for left hemisphere deficits (Shaywitz et al., 2003), it might be expected that coherence between hemispheres would be higher relative to non impaired readers.

The current study examined the early discrimination of word features in a lexical decision task (Waldie & Mosley, 2000) during concurrent EEG in adult English speakers. Much recent research on word reading in dyslexia has been carried out in languages that have close links between phonology and orthography, such as German (Bergmann & Wimmer, 2008), Hungarian (Csepe, et al., 2003), or Finnish (Lyytinen, et al., 2005). As a result some findings may have limited applicability to more complex orthographies such as English.

Here our dyslexic group was age-matched with two comparison groups: monolingual unimpaired readers; and late proficient (English second language) bilinguals. The bilinguals were included for theoretical reasons, as there is some evidence that bilinguals exhibit atypical laterality when performing language tasks in their second language (Badzakova-Trajkov, Kirk, Waldie, 2008; Park, 2009).

Method

Participants

A total of 41 right-handed adults participated in this study. Participants had no known neurological problems and normal (or corrected-to-normal) hearing and vision. The study was approved by the University of Auckland Human Participants Ethics Committee.

Twelve adults with dyslexia were recruited from the University of Auckland Student Learning Centre (female=9). We used the APA diagnostic criteria for dyslexia classification: Difficulties in accuracy or fluency of reading that are not consistent with the person's chronological age, educational opportunities, or intellectual abilities (APA, 2000). The Weschler Abbreviated Scale of Intelligence (WASI; Weschler, 1999) and the Boder Test of Reading-Spelling Patterns

(BTRSP; Boder & Jarrico, 1982) were administered. All participants identified as dyslexic by the Student Learning Centre had a childhood history of severe reading problems, i.e., a reading age at least 2 years below their chronological age, were classified as having dysphonetic dyslexia according to the BTRSP (predominantly phonological processing deficit), and had IQ scores within the normal range.

The monolingual control group (female=10) consisted of fourteen adults selected from the University's staff and students. Fifteen bilingual adults (female=10) were selected from the University's staff and students according to the following criteria: English as a second language after the age of 7 years; currently living in New Zealand; and speaking/reading English proficiently. Demographic details for participants in all three groups are presented in Table One.

Table 1. Mean scores (standard deviations in parentheses) for chronological age (CA), reading age (RA), reading quotient (RQ), performance IQ (PIQ), verbal IQ (VIQ) and Full Scale IQ (FSIQ) as a function of group. Reading Age data was not collected from the Control (unimpaired monolingual adults) or Bilingual Groups.

Group	CA	RA	RQ	PIQ	VIQ	FSIQ
Control (n=14)	28.75 (7.27)	-	-	127.67 (2.58)	119.33 (8.74)	126.67 (4.73)
Bilingual (n=15)	26.59 (6.53)	-	-	113 (7.84)	104.4 (8.59)	109.4 (3.51)
Dyslexic (n=12)	25.04 (6.06)	14.89 (2.22)	69.09 (15.18)	109 (11.93)	108.58 (12.25)	109.66 (11.6)

[*] Not all control subjects obtained IQ scores.

Table 2. Summary of the methodology

Participants in analysis	Tools used	Recruited from:
Adults with dyslexia (n-12)	Diagnostic measures	Student learning centre
Monolingual controls (n=11)		University staff and students
Bilingual adults (n=12)	Quick Placement test	University staff and students
Computer task	Performed by?	Data collected
	All participants	EEG recorded during computer task (lexical decision) - Analysis of accuracy and coherence

Bilingual participants were assessed for English language proficiency using the Quick Placement Test (QPT). This computer based test uses four language tasks (listening, reading, vocabulary and grammar) and calculates a score by adapting the task difficulty in response to individual performance. The QPT produces a language proficiency score out of 100. Bilingual participants in this study were required to be of at least upper intermediate proficiency as indexed by a score of at least 60/100. The bilinguals' first language were Macedonian (n=7), German (n=6), Bulgarian (n=1) and Serbian (n=1) (see Waldie, Badzakova-Trajkov, Milivojevic & Kirk, 2009 for more details).

Stimuli and General Procedure

In the lexical decision task, letter strings were presented in the centre of a computer screen as black capitalised letters on a white background. The stimuli consisted of 60 English words (e.g., GOAT), 30 pronounceble nonwords (e.g., GATO) and 30 unpronounceble nonwords (e.g., GTAO). Each letter string was presented in random order in the centre of the screen for a maximum of 800ms. Participants were required to identify words by pressing the spacebar with their responding hand. No response was required for nonwords (go/no-go paradigm). The next stimulus was presented either after the key press or 2000ms after presentation of the previous stimulus, whichever was sooner. A total of 120 trials were presented in three blocks of 40 letter strings. Participants completed the stimuli list once with each response hand. The order of hands was counterbalanced across participants.

Electrophysiological Recording and Data Analysis

EEG was collected using 128-channel amplifiers from Electrical Geodesics Inc., Eugene, OR, USA (Tucker, 1993). The sample rate was 250Hz with a 0.1 – 100Hz analogue band pass with electrode impedances below 50 KΩ. The EEG data was segmented from -200 to 700ms from stimulus onset and individual waveforms visually inspected for the P1 and N170 components at electrode locations in left and right posterior sites (as shown in Figure 1). The resulting latency and amplitudes from electrodes 65 and 91 were recorded. Recordings from 6 participants were excluded due to poor EEG signals recorded from the electrodes of interest. The resulting group sizes for ERP analysis were dyslexics (N = 12), unimpaired monolinguals (herein referred to as "controls"; N= 11), and bilinguals (N = 12).

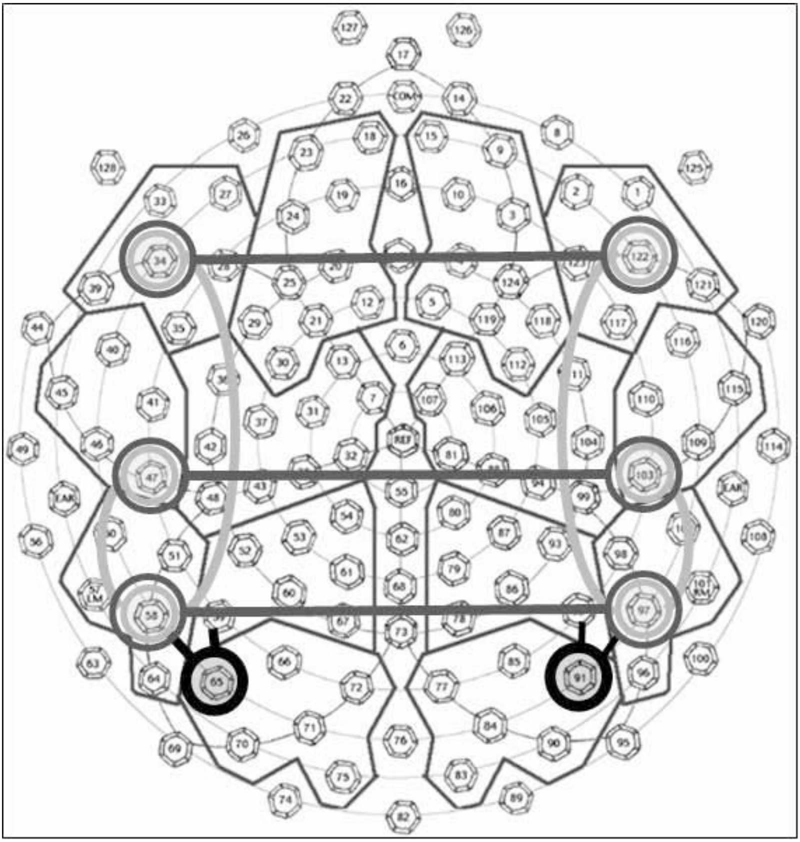


Figure 1. Headmap of the EEG net showing electrodes selected for ERP analysis. P1 and N170 latencies and amplitudes were recorded at electrodes 65 and 91 (black) with reference to two nearby electrodes (black lines) to assist in component identification. Interhemispheric coherence was calculated between electrodes in anterior, medial and posterior locations (marked in medium grey). Intrahemispheric coherence was calculated between electrodes within each hemisphere (marked in light grey).

Calculation of coherence values was conducted using custom in-house software. All participants were included in this analysis. The reference electrode for coherence calculations was changed to linked mastoids as cephalic or average references can distort coherence calculations (French & Beaumont, 1984). The first 511ms of the event-related EEG was subjected to a Fast Fourier Transformation to change the data from the time to the frequency domain. This resulted in a Fast Fourier Transform (FFT) length of 128 and a resolution of 1.92Hz. Pairwise coherence was calculated for seven electrode pairs - three pairs at symmetrical locations in the left and right hemisphere, and two pairs linking anterior-posterior and medial-posterior locations in each hemisphere (as detailed in Figure 1 above). Frequency bins were averaged into four frequency bands of interest: Theta (3.84-7.68 Hz), Alpha (9.6-13.44Hz), Beta (15.36-30.72Hz), and Gamma (32.64-42.24Hz).

SPSS Version 16 was used for analyses and the alpha level for significance was .05. Mauchley's Test of Sphericity was performed on the data to check for the assumption of sphericity when performing Split-plot Analysis of Variance (SPANOVA). Where violations of sphericity occurred, statistics were reported with Greenhouse-Geisser corrections. Pairwise comparisons were analysed with a Bonferroni adjustment to the alpha level (e.g., the significance level was changed to α / k to follow-up significant main or interaction effects to counteract the problem of multiple comparisons). The Bonferroni correction is considered the simplest and most conservative method to control the familywise error rate (to limit the possibility of Type I error). The Kruskall-Wallis Test was used for Group analyses if data screening indicated violations of parametric assumptions. As there were no effects of Nonword Type (pronounceable nonwords, unpronounceable nonwords) in preliminary analyses, nonwords data was combined in analyses.

Results

Behavioural Data

As shown in Table 3, the dyslexic group was significantly slower to respond using both the right and the left hand compared to both the control and bilingual groups.

Table 3. Median time (in ms) taken to respond to the lexical decision stimuli by Group and Response hand (standard deviations in parentheses).

Group	**Left Hand**	**Right Hand**
Control	544.6 (475.37)	533.36 (839.15)
Bilingual	572 (284.61)	594.4 (207.87)
Dyslexic	699.16 (475.06)*	685.87 (404.26)**

*Dyslexics were significantly slower than controls (*U*=37.50, p=.016) and bilinguals (*U*=49.00, p=.045).

**Dyslexics were significantly slower than controls (*U*=30.00, p=.005) and bilinguals (*U*=40.50, p=.015).

Accuracy data was analysed using a 3 (Group) by 2 (Word type) SPANOVA. Analysis revealed a significant main effect of Group ($F_{(2,38)}$= 16.30 p<.001) and Word type ($F_{(2,38)}$= 49.57, p<.001). As shown in Figure 2, there was a Group by Word interaction ($F_{(2,38)}$= 10.98, p<.001). Simple effects tests revealed that, for *words* and *nonwords*, dyslexics were significantly less accurate than both the control (both p's <.03) and bilingual (both p's <.03) groups. For nonwords only, bilinguals were significantly less accurate than controls (p=.027).

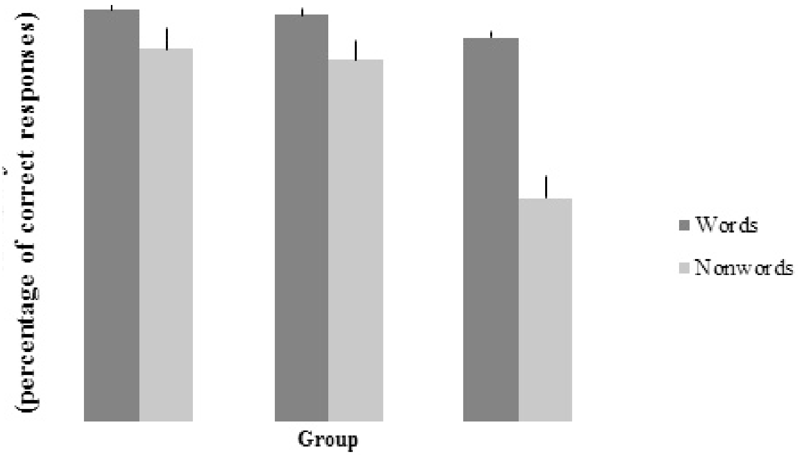
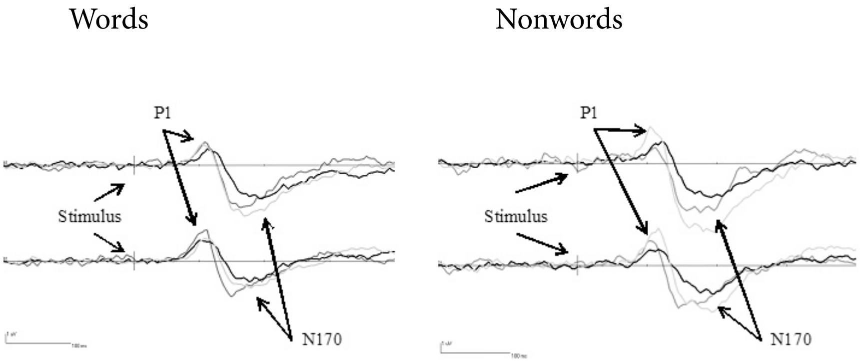


Figure 2. Bar graph showing the accuracy (error bars represent + 1SE) for identifying words and nonwords as a function of group.

ERP Analysis

Figure 3 shows the ERP waveform responses averaged across each group. Individual ERP latency and amplitude scores were subjected to a 3 (Group) x 2 (Word type) x 2 (Hemisphere) SPANOVA. The within subject variables were Word type (words, nonwords) and Hemisphere (left, right). Simple effects tests were conducted separately for the left and right hemispheres in the case of a significant 3-way interaction.


Words

Nonwords

Figure 3. ERP waveform responses to word (left) and nonword (right) stimuli. Each line represents a group average (control – medium grey, bilingual – light grey, dyslexic – black). Responses from the left (electrode 65, top) and right (electrode 91, bottom) posterior electrodes are shown. The dyslexic waveforms (black) show a flattened N170 peak in both conditions and at both electrodes.

P1 Latency

There was a significant Group difference in P1 latency ($F_{(2,32)}$= 3.43, p=.045) whereby dyslexics were slower ($\underline{M}$=122.25, SE=2.79) than controls ($\underline{M}$=112.55, SE=2.91) to respond to words/nonwords. No other significant effects were found.

P1 Amplitude

There were significant main effects of Group ($F_{(2,32)}$= 6.30, p= .005), Hemisphere ($F_{(2,32)}$= 6.26, p= .018) and Word type ($F_{(2,32)}$= 5.13, p= .031). There was also a significant Group by Hemisphere by Word type interaction ($F_{(2,32)}$= 6.86, p= .003). For the left hemisphere, there were higher amplitudes in response to *nonwords* than to words for controls (p = .024) and bilinguals (p = .002). Dyslexics showed no amplitude differences. For the right hemisphere there was a significant group differences for *words* only ($F_{(2,32)}$= 7.12, p = .003). Amplitudes were significantly higher for bilinguals than for both controls (p = .047) and dyslexics (p = .003). There were no amplitude differences between dyslexics and controls. Examination of the effect of word for each group found no differences between responses to words and nonwords for any of the three groups.

N1 Latency

There was a main effect of Group ($F_{(2,32)}$= 3.92 , p= .030) with dyslexics (M= 194.25, SE= 6.77) having significantly slower N1 latencies than controls (M= 167.00, SE= 7.07, p= .027). No significant differences were found between bilinguals (M= 178.75, SE= 6.77) either in the control or dyslexic groups. No other main or interaction effects were found.

N1 Amplitude

There was a significant effect of Group on the amplitudes of the N1 component ($F_{(2,32)}$= 15.05, p<.001). There was also a main effect of Word type ($F_{(2,32)}$= 21.58, p<.001). There was a significant Group by Hemisphere by Word type interaction ($F_{(2,32)}$= 5.96 , p= .006). For the left hemisphere there was a significant group differences for *words* only ($F_{(2,32)}$= 23.06, p <.001). Bilinguals showed significantly higher amplitudes than both controls (p <.001) and dyslexics (p <.001). Words elicited a significantly lower amplitude than nonwords in the dyslexic (p <.001) group. For the right hemisphere there was a significant group effect for *words* only ($F_{(2,32)}$= 47.13, p <.001). Dyslexics had lower amplitudes than both the control (p <.001) and bilingual (p <.001) groups. Examination of the effect of word type for each group indicated that *dyslexics* had a significantly lower N1 amplitude response to words than nonwords (p <.001). There were no differences between responses to words and nonwords for either control or bilingual readers.

Interhemispheric coherence

Group means within each frequency band are shown in Figure 4. Event-related coherence scores for pairs at symmetrical locations in both hemispheres were subjected to a Group by Word by Location by Frequency band SPANOVA. The within subjects variables were word type (words, nonwords), electrode pair location (anterior, medial, posterior) and frequency band (theta, alpha, beta, gamma). The analysis revealed significant Group differences for interhemispheric coherence within the theta ($F_{(2,38)}$= 4.37,p=.020) and gamma ($F_{(2,38)}$=3.85, p=.030) frequencies but not within the alpha and beta bands.

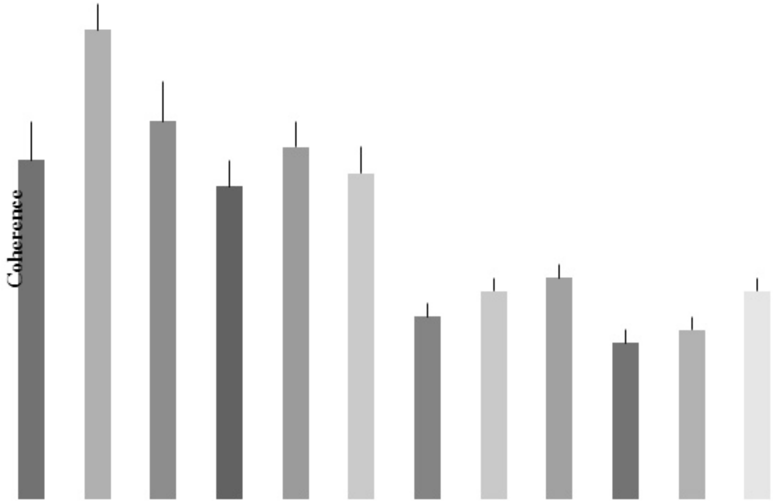


Figure 4. Bar graph showing mean (error bars represent +1 SE) interhemispheric coherence within each frequency band. Note: * p<.05.

Theta

There was a main effect of Group ($F_{(2,38)}$=4.37, p=.020) with bilinguals having significantly higher coherence (M=.36, SE=.02) than controls (M=.26, SE=.03, p=.019). There were no differences between dyslexics (M=.29, SE=.03) and either controls or bilinguals. A main effect of Location was also found ($F_{(2,59)}$= 61.51, p<.001) with the anterior electrode pair having stronger coherence (M=.45, SE= .03) than both the medial (M=.17, SE=.02, p<.001) and posterior (M=.28, SE=.02, p<.001) pairs. There was also a main effect of Word ($F_{(1,38)}$= 7.54, p=.009). Stronger coherence was recorded in response to nonwords (M=.31, SE=.01) than to words (M=.29, SE=.01). No interaction effects were found.

Gamma

There was a main effect of Group ($F_{(2,38)}$=3.85, p=.03). Dyslexics (M=.16, SE=.01) had a significantly stronger coherence than controls (M=.12, SE=.01, p=.035). There were no other significant differences. There was also a main effect of Location ($F_{(2,76)}$=6.12, p=.003). Coherence across anterior electrodes (M=.17, SE=.01) was significantly stronger than across medial electrodes (M=.10, SE=.01, p=.005). Posterior coherence (M=.14, SE=.01) was slightly weaker than anterior and slightly stronger than medial (both p>.05). A main effect of Word was also found ($F_{(1,38)}$=27.43, p<.001) with higher coherences elicited by nonwords (M=.15, SE=.01) than by words (M=.12, SE=.01). There were no significant interactions.

Intrahemispheric coherence

Group means within each frequency band are shown in Figure 5. Event-related coherence scores for pairs at locations within each hemisphere were subjected to an omnibus Group by Word by Location by Frequency band SPANOVA. The only group differences for intrahemispheric coherence occurred within the theta ($F_{(6,114)}$= 4.20,p=.005) frequency.

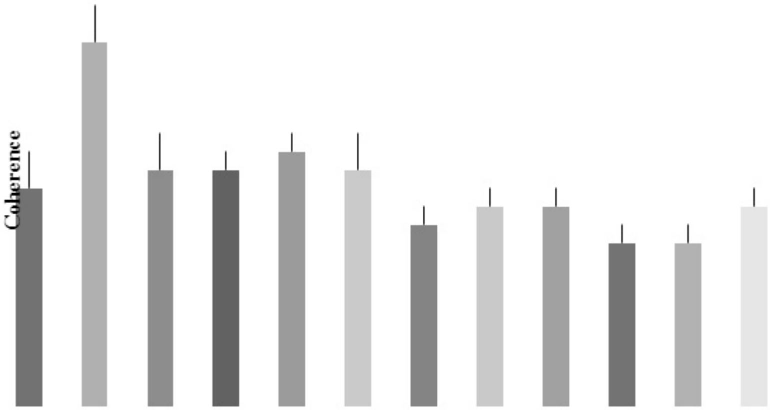


Figure 5. Bar graph showing mean (error bars represent +1 SE) intrahemispheric coherence within each frequency band. Note: * p<.05.

Theta

A main effect of Group was found ($F_{(2,38)}$= 4.96, p=.012). Theta coherence was significantly stronger for bilinguals (M=.20, SE=.02) than for controls (M=.12, SE=.02, p=.019). Dyslexics' coherence values (M=.13, SE=.02) were not significantly different from controls or bilinguals. A main effect of Location occurred ($F_{(1,38)}$= 19.21, p<.001). There was stronger coherence between medial-posterior electrode pairs (M=.18, SE=.02) than between anterior-posterior pairs (M=.11, SE = .01). A main effect of Word was found ($F_{(1,38)}$=6.32, p=.016) with stronger coherence to nonwords (M=.16, SE=.01) than to words (M=.14, SE =.01).

Table 4 presents a summary of the behavioural and EEG results. In sum, dyslexics had a significantly lower amplitude N170 response than nonimpaired readers, particularly in response to words. Their responses were also significantly slower. When compared to monolinguals, bilinguals had significantly higher amplitude for the N170 in the left hemisphere. For the P1 component, latency was slower for dyslexics than other groups. Bilinguals had significantly higher P1 amplitude responses to words at the right electrode. For the coherence data, dyslexics showed significantly higher synchrony between hemispheres in the gamma frequency band than the unimpaired groups. When compared to monolinguals, bilinguals had significantly higher coherence both between and within hemispheres in the theta frequency band.

Table 4. Summary of results.

Dependent Variable	Highest order effect	*Interpretation*
Accuracy	Group X Word	Dyslexics less accurate for all verbal stimuli than other groups
EEG PI Latency	Group main effect	Dyslexic slower to respond to stimuli than controls
EEG PI Amplitude	Group X Hemisphere X Word type	Left hemisphere: amplitudes higher for words than nonwords except for dyslexics Right hemisphere: higher amplitudes for words for bilinguals than other groups
EEG N1 Latency	Group main effect	Dyslexic slower to respond to stimuli than controls

EEG N1 Amplitude	Group X Hemisphere X Word type	Left hemisphere: amplitudes higher for bilinguals for all stimuli than other groups Right hemisphere: lower amplitudes for all stimuli for dyslexics than other groups. Amplitude was also lower for words than nonwords just for dyslexics.
Theta coherence between hemispheres	Main effects of Group, Location, Word type	Bilinguals showed stronger coherence than controls
Gamma coherence between hemispheres	Main effects of Group, Location, Word type	Dyslexics showed stronger coherence than controls
Theta coherence within hemispheres	Main effects of Group, Location, Word type	Bilinguals showed stronger coherence than controls

Discussion

The purpose of this study was to examine lexical decision making among English speaking adult dyslexics using scalp recorded EEG event-related potentials and coherence. Comparison groups included unimpaired monolingual readers and unimpaired (late proficient) bilingual readers. Participants responded with a key press when the (centrally presented) letter string was a word and did not respond to nonword stimuli (i.e. go/no-go response). Behavioural responses to the task (reaction time and accuracy) were also acquired and indicated that dyslexic participants were both slower to respond and less accurate than the non reading-impaired groups.

Event-Related Potentials

The primary finding from the ERP data was that, compared to unimpaired readers, dyslexics showed a significantly smaller N170 amplitude response. This component also occurred significantly later than in the other two groups. This finding is consistent with a study by Breznitz (2003) with adult Hebrew dyslexics on a word reading task. The reduced amplitude is also consistent with a recent study of dyslexic German children (Kast, et al., 2010). Increased amplitude has previously been attributed to more effortful processing (Csepe, et al., 2003). One possible interpretation of reduced amplitude is that of *less effortful* processing. This may be due to a disruption in underlying structures. In this case, a failure to activate the areas commonly linked to visual word form (as would be expected in a visual lexical decision task) could result in reduced activity in the posterior electrodes examined here. An alternative view may be that the reduced N170 amplitude may simply reflect dyslexics' use of different cortical areas to perform the task.

Reduced amplitude might also be due to *less co-ordinated* effort (asynchrony of neuronal activity). According to this interpretation, slowed processing causes a mismatch when combining the orthographic and phonologic aspects of words in memory (Breznitz & Meyler, 2003; Meyler & Breznitz, 2005). Two results in the present study would support such an interpretation for the dyslexic group. Firstly, slower speed of neural processing can be inferred from the P1 and N170 latencies. For dyslexics, the earlier P1 component was slightly delayed compared to the other groups, whereas the N170 peak was significantly more delayed. Secondly, visual examination of the group average ERP waveform shows a broader peaked N170 for dyslexics than for controls.

The low N170 amplitude in this study for dyslexics was particularly noticeable in response to words (rather than nonwords). The reasons for this are not clear. As previously mentioned, the N170 is sensitive to word form (Nobre, et al., 1994). An increase in the N170 amplitude in normal readers to frequent or highly repeated words in lexical decision tasks are likely to reflect holistic (visual word form) processing of words (Simon, Petit, Bernard, & Rebai, 2007). In the dyslexic group, the lower N170 in response to words might therefore be interpreted as a failure to identify the visual aspects of word form. This would be consistent with other electrophysiological investigations, such as those by Salmelin and co-workers (Salmelin, 2007; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996), who proposed that dyslexics were not benefiting from access to a sight word lexicon at the early stage of information processing.

One unexpected finding in this study was that the usual left greater than right activation generally found in response to word reading tasks in normal readers did not occur. For the control and bilingual groups, the amplitudes of the P1 and N170 were higher in the right hemisphere than in the left. An explanation for this may be that the specific requirements of this experimental task encouraged a processing strategy that is more efficiently performed using right hemisphere resources. Voyer (2003) investigated laterality effects specifically within lexical decision tasks and concluded that participants were determining whether the word was visually familiar rather than fully accessing the word form. The author noted that this strategy may be specific to task requirements in lexical decision.

The response paradigm used in the current study may have encouraged such a strategy. For example, a left greater than right amplitude difference has been found (Simon, et al., 2007). Unlike the current study (go/no-go paradigm), participants had to respond by pressing one button for words and another for nonwords. Kast et al. (2010) used a go/no-go response paradigm and found bilateral N170 processing. Our participants may have simply determined whether the stimuli were visually familiar. Reduced N170 processing in the dyslexic group indicates that deficits occur even when lexical decision-making tasks encourage discrimination based only on visual familiarity.

For the P1 component, dyslexics did not differ significantly from unimpaired readers. This is consistent with previous research discussed earlier (Breznitz, 2003). Bilinguals had higher P1 amplitude in the right hemisphere in response to words compared to monolingual controls. One interpretation of higher amplitude for bilinguals at this component might be that, because English is their second language, more effort was needed to discriminate word features than required by monolinguals.

Coherence analysis

Coherence measures the degree of synchrony in the frequency spectrum between neuronal assemblies. In this study coherence was measured pairwise between individual electrodes. Higher coherence between the two cerebral hemispheres (inter-hemispheric coherence) was expected for dyslexics because of claims that dyslexics use compensatory right hemisphere resources to access word form (Shaywitz & Shaywitz, 2005; Waldie, 2002). Synchrony within the left hemisphere was expected to be lower in dyslexics than in unimpaired readers as is suggested by connectionist models of dyslexia (Pugh, et al., 2001). Within interhemispheric electrodes (but not between intrahemispheric electrodes), dyslexics exhibited higher coherences in the gamma frequency band. This is a novel finding. A previous study in adult dyslexics found *lower* interhemispheric synchrony within the alpha band in a visual discrimination task (Dhar, et al., 2010). One reason for inconsistencies between this study and previous finding may be differences in the experimental tasks used.

Significant coherence effects were also found with our late proficient bilingual group. Bilinguals exhibited higher coherence than monolinguals on measures of both inter and intrahemispheric communication within the theta frequency. Theta activity correlates with memory functions in word reading tasks (Weiss & Mueller, 2003). There are few investigations into bilingualism using coherence measures. Studies thus far have focussed on the differences within bilingual groups differentiated on the basis of the age of second language acquisition or proficiency (Reiterer, Hemmelmann, Rappelsberger, & Berger, 2005; Reiterer, Pereda, & Bhattacharya, 2009).

The gamma frequency band has been linked with feature binding, mental integration and gestalt perception as well as higher cognitive mental states, such as language processing (Basar, 2005; Reiterer, et al., 2009). Gamma frequencies have traditionally not been included in coherence studies of word reading or dyslexia (Reiterer, et al., 2009). For example, Leisman and Ashkenazi (1980) only measured frequencies to 32Hz. Recent discoveries of the importance of gamma activity to the formation of memory and working memory has led to a resurgence of interest in gamma band activity (Debner, Herrmann, Kranczioch, Gembris, & Engel, 2009; Jutras & Buffalo, 2010; Reiterer, et al., 2009; Senkowski, Schneider, Tandler, & Engel, 2009)

Gamma has most recently been related to theta band activity and the two are now considered to be critical to memory formation and working memory (Jutras & Buffalo, 2010). Activity in theta and gamma frequencies combines to form the structure of individual memories. Gamma activity within close neuronal networks is organised by theta activity (Lisman & Idiart, 1995). The exact role of gamma and theta in word reading is not yet fully understood. Some relate theta to a neural representation of concepts and words (Penolazzi, Spironelli, Vio, & Angrilli, 2006) and gamma to the visual gestalt of a word (von Stein & Sarnthein, 2000). Others interpret gamma band coherence as matching semantic information in memory with multisensory input (Debner, et al., 2009; Senkowski, et al., 2009). Overall, it appears that gamma band activity relates to access to word information in memory and may involve higher level cognitive features than theta activity.

High gamma band coherence has also been associated with poor language ability. In a study of bilinguals varying in their level of second language proficiency, coherence within the lower gamma band (30-40Hz) was highest for low proficient bilinguals (Reiterer, et al., 2009). They interpreted gamma coherence as relating to an increased involvement of right hemisphere resources in reading. Reiterer et al. (2005) noted that there was no agreement about *why* right hemisphere involvement is observed with low proficiency bilinguals. One suggestion was that low proficient bilinguals engaged in holistic learning strategies which placed greater reliance on right hemisphere systems compared to proficient bilinguals. Similarly, the higher gamma synchrony between hemispheres in dyslexics may be due to a greater use of right hemisphere resources, as has been hypothesised.

Enhanced right hemisphere involvement (inferred by higher interhemispheric synchrony on this task) may be explained by greater selective attention when perceiving word-like strings. Debner et al. (2009) found that selective attention enhances activity in the gamma frequency. Selective attention (or vigilance) is a top down process whereby expectations enhance incoming sensory information (Sarter, Givens, & Bruno, 2001). It interacts with bottom-up processes to optimise performance in complex tasks. Selective attention is often associated with right hemisphere activity.

The expected low synchrony between left hemisphere electrodes for dyslexics was not observed. A recent study found lower intrahemispheric coherence in the delta and beta frequencies and higher alpha frequencies in children (Barry, et al., 2009). One reason for inconsistencies between studies may be due to developmental changes in coherence, as the earlier finding was in children. Age related changes in event-related gamma coherence have been reported in normal readers (Heinrich, Kolev, Rothenberger, & Yordanova, 2009).

The pattern of higher interhemispheric (but not *intra*hemispheric) coherence found in dyslexics in this study could also be explained by features specific to the gamma frequency. Gamma band coherence is limited to synchronisation in local neuronal networks and to areas joined by monosynaptic connections, such as the corpus callosum (von Stein & Sarnthein, 2000). This is because high frequency gamma oscillations degrade over longer distances. Memory interactions between more distant areas are linked with activity in the theta band. A higher reliance by dyslexics on gamma frequency processing would increase gamma coherence but only for interhemispheric networks as the gamma signal would degrade over the intrahemispheric distance.

Summary and Conclusions

This study has made some useful contributions to understanding the time course of word reading. Firstly, it contributes to current ERP literature by finding similar deficits in N170 processing within a group of adult English speaking dyslexics as have been found in more complex orthographies. Secondly, the inclusion of late proficient bilinguals as a comparison group helped to highlight variations in atypical language processing in both groups. Finally, for the first time we report higher gamma frequency synchrony between hemispheres in the dyslexic group.

In conclusion, dyslexics showed a reduced N170 amplitude response in this lexical decision task, particularly in response to words. This is likely due, in part, to an asynchrony of neuronal activity at the point where word form features are distinguished. Specific response requirements in this task encouraged normal readers to rely on visual familiarity of the image (rather than accessing word form) when discriminating between word and nonwords stimuli. Reduced N170 activation in the dyslexic group indicates that deficits occur even when lexical decision-making tasks encourage visual familiarity only. Dyslexic participants also demonstrated higher synchrony of neuronal activity between hemispheres in the gamma band compared to nonimpaired readers. This highlights the importance of investigating gamma band activity in word reading and particularly in studies of dyslexia.

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