

# Altered hemispheric specialization for speech in adult dyslexic readers: An ERPs and dichotic listening study

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## ABSTRACT

The aim of this study was to investigate the functional speech lateralization in adult dyslexic readers whose native language is Hebrew. Event-related potentials (ERPs) were recorded from 22 non-impaired readers and 18 dyslexic readers performing dichotic nonsense consonant-vowel (CV) syllables and dichotic vowels target detection tasks. Evidence of altered patterns of behavioral speech lateralization was found in the dyslexic group mainly for the CV syllables task. The latencies and amplitudes of the N1–P2 ERPs complex produced by the dichotic CV syllables and dichotic vowels tasks were deviant as well. The findings suggest a differently organized auditory system with altered speech lateralization in adult dyslexic readers.

## 1. Introduction

Dyslexia is a specific learning disability with a neurobiological origin, characterized by difficulties in word recognition and poor spelling despite adequate classroom instruction. These difficulties are assumed to be outcomes of phonological deficits. Secondary consequences may include difficulties in reading comprehension, reduced reading experience, limited vocabulary and background knowledge (Lyon, Shaywitz, & Shaywitz, 2003).

The research into developmental dyslexia looks for neuropsychological deficits that might explain the clinical manifestations in poor readers (Heim, Eulitz, & Elbert, 2003; Illingworth & Bishop, 2009; Larsen, Høien, Lundberg, & Ødegaard, 1990). Since Orton (1925) suggested atypical hemispheric specialization for speech in dyslexia, the subject has been studied using various methods (Bloom, Garcia-Barrera, Miller, Miller, & Hynd, 2013; Kershner, 2016; Xu, Yang, Siok, & Tan, 2015).

Dichotic listening (DL) is a noninvasive paradigm used frequently in the research of auditory lateralization. It involves the simultaneous presentation of two different auditory stimuli, one in each ear (Bryden, 1988a; Hugdahl, 2003; Obrzut & Boliek, 1988). Broadbent (1954) originally developed the technique of DL to study selective attention, and Kimura (1961a, b) modified it in the form it is used today. The typical finding in non-impaired participants is a right ear advantage (REA) for speech stimuli, which means that more stimuli are correctly reported from the right ear than from the left ear. The REA induced by speech stimuli in DL is believed to reflect the speech specialization of the left hemisphere and is a robust empirical finding in both right-handed and left-handed non-impaired readers (Helland & Asbjørnsen, 2001; Hugdahl, 2003).

While non-reading impaired children typically show the REA in DL studies (Andersson & Hugdahl, 1987; Brunswick & Rippon, 1994; Helland & Asbjørnsen, 2001), children diagnosed with dyslexia demonstrate inconsistent speech lateralization patterns across studies. Several studies found no ear advantage (NEA) in dyslexic readers, whereas non-impaired readers demonstrated a REA for speech stimuli (Witelson, 1976; Zurif & Carson, 1970). In other studies, reduced patterns of asymmetry were found in dyslexic readers

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compared to non-impaired readers (Cohen, Hynd, & Hugdahl, 1992; Helland & Asbjørnsen, 2001; Martínez & Sánchez, 1999). Agrawal and Valame (2011) reported an increased REA in children diagnosed with dyslexia compared to non-impaired children. Finally, Kumar and Gupta (2015) found a left ear advantage (LEA) for children with dyslexia, whereas non-impaired children showed a significant REA.

Event-related potentials (ERPs) is an electrophysiological technique used to analyze the neural changes caused by information processing in the brain with high temporal resolution (Breznitz & Meyler, 2003; Guttorm, Leppanen, Richardson, & Lyytinen, 2001). While ERPs in conjunction with DL may be utilized to study functional speech lateralization, only a few studies have combined electrophysiological techniques simultaneously with the DL paradigm for this purpose, and most of them focused on non-impaired readers.

A few studies used ERPs combined with DL in order to study speech lateralization in non-impaired children and children diagnosed with dyslexia. Brunswick and Rippon (1994) compared the auditory evoked potentials (AEPs) produced by dichotic stop consonant-vowel (CV) syllables in dyslexic readers and non-impaired readers. They found no differences between the groups for the DL. However, the non-impaired readers displayed significantly greater N1 amplitudes in the temporal region of the left hemisphere, while the dyslexic readers showed a symmetrical amplitude for this component. The authors concluded that dyslexic readers are characterized by abnormal cerebral lateralization for language. In another research, Johnson et al. (2013) presented broadband noises (noise only and dichotic pitches) to non-impaired readers and dyslexic children while recording their electroencephalography (EEG) and magnetoencephalography brain measurements. The non-impaired readers were characterized by a strong lateralization, while the dyslexic children showed significantly less lateralization of the auditory cortical functioning. The researchers suggested that the core neurophysiological deficit in dyslexia is a deficient balance of auditory functioning between the two hemispheres.

DL studies conducted in adult dyslexic readers demonstrated mixed results, while the REA for syllables stimuli is a typical finding in non-impaired readers (Bryden, 1988b). For example, Iliadou, Kaprinis, Kandylis, and Kaprinis (2010) found NEA in dyslexic readers, while non-impaired readers showed a REA for speech stimuli. Hugdahl, Helland, Færevag, Lyssand, and Asbjørnsen (1995) found reduced asymmetry in adult dyslexic readers compared to non-impaired adult readers.

Several studies recorded ERPs while non-impaired adult readers engaged in DL. Neville (1974) recorded AEPs to dichotic verbal and nonverbal auditory stimuli. There were no significant differences in the accuracy of the reports for nonverbal stimuli, whereas verbal stimuli were identified more accurately from the right ear than the left ear. In addition, early AEPs components for verbal stimuli showed greater amplitude and shorter latencies on the left hemisphere than the right hemisphere. Nonverbal stimuli yielded inconsistent latency and amplitude patterns. In another study, Ahonnikka, Cantell, Tolvanen, and Lyytinen (1993) introduced dichotic CV syllables to stable REA and LEA participants. They found enhanced P3 amplitude for the left hemisphere in the REA group and a reversed laterality pattern for the LEA group. Van de Vijver, Kok, Bakker, and Bouma (1984) introduced dichotic digits to right ear and LEA groups and found a more positive late component on the left hemisphere, with no correlation between the ear advantage and hemispheric asymmetry. Eichele, Nordby, Rimol, and Hugdahl (2005) recorded AEPs from non-impaired participants who performed a free report DL task with CV syllables. The latency of the N1-AEPs related to the left supratemporal region was shorter than the homologous site on the right hemisphere.

The research applied ERPs while adult dyslexic readers performing DL tasks is limited. Sebastian and Yasin (2008) used EEG to study the mismatch negativity measured for both dichotic speech stimuli (CV syllables) and dichotic non-speech stimuli (pure tones) in undergraduate and postgraduate non-impaired and dyslexic readers. They found less mismatch negativity with regard to the tone stimuli in the dyslexic readers than the non-impaired readers, but no differences for the speech stimuli. The researchers suggested that in dyslexia the auditory system might show less specialization for different categories of stimuli.

Despite a growing literature related to hemispheric specialization for speech in dyslexic readers, few examined the association between reading and hemispheric specialization for speech in adult dyslexic readers by combining DL technique and ERPs. There is increasing recognition that differences in the magnitude of ear advantage in individuals are an important aspect of DL performance. Some of these differences are related to individual variations in the degree of cerebral lateralization (Bruder, 1983; Repp, 1977; Shankweiler & Studdert-Kennedy, 1975). With regard to the ERPs, the methodology provides noninvasive approach to study psychophysiological correlates of cognitive processes (Sur & Sinha, 2009). The ERPs are generated in the brain in response to specific events or stimuli (Blackwood & Muir, 1990) and they are thought to reflect the summed activity, or synchronized firing neurons while processing information (Peterson, Schroeder, & Arezzo, 1995). Taken together, the combination between DL and ERPs may be useful for investigating hemispheric specialization for speech in adult dyslexics.

The aim of this study was to explore the functional speech lateralization in adult dyslexic readers by identifying electrophysiological correlates of dichotic speech stimuli. Participants engaged in two dichotic target detection tasks including low-level pre-lexical stimuli. One task included nonsense CV syllables and the other task contained vowels. The target detection tasks were applied to avoid potential speech movement which may distort the EEG signals (Brooker & Donald, 1980; Szirtes & Vaughan, 1977), and to record reaction time measures.

A main focus was given to the N1–P2 complex. The N1–P2 may represent the activation of neural assemblies involved with the analysis of incoming auditory stimuli (Picton & Hillyard, 1974). The N1 is a negative deflection peaking between 90 and 200 ms (ms) after the onset of a stimulus. It is observed when an unexpected stimulus is presented. The P2 refers to a positive deflection peaking around 100–250 ms after the stimulus. The two ERPs components may reflect perceptual processes (McPherson, 1996; Moisescu-Yiflach & Pratt, 2005; Sur & Sinha, 2009). It was hypothesized that the dichotic CV syllables will produce a lower functional auditory asymmetry in the dyslexic readers compared to the non-impaired readers. In addition, it was hypothesized that none of the groups would show significant laterality effects for dichotic vowels.

## 2. Method

### 2.1. Participants

Participants were native Hebrew-speaking students at the University of Haifa. The non-impaired group consisted of 22 participants (11 males and 11 females, mean age 25.4 years, SD = 3.35), recruited through advertisements posted throughout the university. The dyslexic readers group consisted of 18 participants (9 males and 9 females, mean age 26.4, SD = 4.37), recruited through the university's student services office. All of the participants were matched for age and general ability. All were right-handed, and none reported a history of neurological deficits, psychiatric disorders, or significant hearing complaints. All students were paid volunteers.

### 2.2. Background measures

The classification of participants into non-impaired readers and dyslexic readers was validated by the following tests:

*Raven's Standard Progressive Matrices* (Raven, 1960): The test was used to assess general ability. Raw scores were recorded for each participant.

*One Minute Tests*: This battery measured decoding skills and included two subtests in which participants were asked to read single words as quickly and accurately as possible in 1 min. The *One Minute Test for Words* (Shatil, 1997a) contained 100 real words arranged in order of increasing length and decreasing frequency. The *One Minute Test for Pseudowords* (Shatil, 1997b) included 100 pseudowords arranged in order of increasing length. Accuracy scores were based on the number of words or pseudowords read correctly. Reading rates were calculated on the basis of the number of words read in 1 min.

*Reading Comprehension Test* (The Center for Psychometric Tests, 1994): Participants were asked to read aloud a passage as quickly as possible, then answer 5 multiple-choice questions and 12 yes/no questions. Reading time was based on mean reading time per word. Comprehension scores were based on the total number of correct answers.

*Phonemic Deletion Test* (Shatil, 2001b): The test was used to evaluate phonemic awareness. The participants were presented with 25 pseudowords read aloud by the experimenter, and the participants were asked to vocalize each pseudoword by omitting a designated phoneme located at the beginning, the middle, or the end of the word. Average time per item and average accuracy were recorded.

*Parsing Test* (Breznitz, 1997b) and *Dictation Test* (Shatil, 2001a): The two tests assessed the orthographic skills of each group. The *Parsing Test* involved the presentation of a list that included 46-character strings, each consisting of a number of words. The participants were asked to parse each string into its constituent words by marking vertical lines between the words. The total time of the test and the number of correctly parsed strings were recorded. The *Dictation Test* required writing 30 Hebrew words that were read aloud by the experimenter. The total number of errors was recorded.

*Digit Span* (WAIS III, Wechsler, 1994) and *Working Memory-Opposites* (Shani & Ben-Dror, 1998): The two tests were used to evaluate memory functions. In the *Digit Span* test, the standard scores of each participant were recorded for the forward and backward parts. The *Working Memory-Opposites* consisted of a series of adjectives containing approximately the same number of syllables in Hebrew, each of which had an opposite (for instance, tall/short; big/small; black/white). The adjective series appeared in sets of two, and were presented in order of increasing length. The number of adjectives in each series of each set ranged successively from 2 to 8 adjectives. Each series of adjectives was read aloud by the experimenter, one at a time, after which the participant was required to respond with the opposite of each adjective in the series, in the order in which the adjectives were given (for instance, the response to "tall-big-black" would be "short-small-white"). The test ended when a participant failed on two consecutive adjective sequences within the same set. The test was not time limited, and scores were based on the number of correct responses.

*Rapid Automatized Naming* (RAN) (Breznitz, 1997a, based on; Denckla & Rudel, 1976) and *Verbal Fluency Test* (Breznitz, 1996; designed on the basis of; Lezak, 1993): The tests were used to assess the verbal speed of processing. In the RAN tests participants were instructed to name a list of 50 recurring Hebrew characters and a list of 50 recurring objects as quickly and as accurately as possible. Time and number of errors were recorded for each list. In the *Verbal Fluency Test* participants were requested to verbally generate lists of words, each beginning with a given Hebrew letter ('Bet' {b}, 'Resh' {r}, and 'Shin' {sh}). One minute was given for each list. The score was the sum of the words recalled for each letter.

*Symbol Search Test* (WAIS III, Wechsler, 1994): Average standard scores were recorded in order to evaluate attentional functions.

### 2.3. Dichotic target detection tasks

Dichotic nonsense CV syllables and dichotic vowels tasks were created to study hemispheric specialization for speech in both groups. All stimuli were read through a microphone by a male voice (a native Hebrew speaker) with constant intonation and intensity. The recordings were digitized for editing on a computer equipped with a standard sound board. Each pair of stimuli was aligned using GoldWave v5.05 software (GoldWave Inc., 2003) to control the duration of the stimulus and the synchronization of simultaneous onset time. Stimuli were presented at 75 dB through closed-system headphones.

*Dichotic Consonant-Vowel Syllables Task*: The dichotic syllables consisted of six stop consonants paired with the vowel/a/ to form the CV syllables/ba/,/da/,/ga/,/ka/,/pa/,/ta/. Combinations of two CV syllables were made with a total of 200 dichotic pairs presented to the participants. Homonymic pairs were excluded. The duration of each dichotic CV stimulus was 380 ms, and the interstimulus interval was 2500 ms. The syllable/ka/served as a target, while 100 targets were presented to the right ear and 100 to

the left ear.

**Dichotic Vowels Task:** The dichotic vowels consisted of combinations of the vowels /a/, /e/, /i/, /o/, /u/. A total of 200 dichotic vowels were presented with a duration of 320 ms each. The interstimulus interval was 2500 ms and homonymic pairs were excluded. The vowel /a/ served as a target stimulus; 100 target stimuli were presented to the right ear, and 100 to the left ear.

#### 2.4. EEG recordings

The EEG was recorded using the following 31 scalp electrodes according to the international 10/20 system (Jasper, 1958): Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2, Fpz, AFz, FC1, FC2, FC5, FC6, CP1, CP2, CP5, CP6, PO3, and PO4. Scalp electrodes were referenced to an electrode on the chin and grounded to an electrode on the mastoid. Eye movements were monitored by a separate electrode placed below the left eye. EEG data were sampled at 256 Hz, using a Ceegraph XL collection system (Bio-Logic Systems, Corp., Mundelein IL). During data collection, electrode impedance was kept below 5 K $\Omega$  by first prepping scalp areas with a mildly abrasive cleanser (NuPrep) and then using an electrolyte gel (Electro-gel). Signals were filtered at 0.1–100 Hz. Continuous EEG recordings were segmented into 1.75-s epochs (448 samples, fs = 256 Hz). Each epoch contained 64 pre-stimulus samples (= 250 ms) for establishing baseline activity and 384 post-stimulus samples. Baseline correction was performed using the EEGLab toolbox for MATLAB (v.4.512- Swartz Center for Computational Neuroscience, UCSD). Epochs were visually inspected, and those displaying eye movements between 0 ms and 600 ms after stimulus onset, saturation values in one channel or more, high noise levels, or incorrect responses were rejected. Epochs containing eye-blinks during baseline were also rejected. The remaining epochs were separated based on stimulus type.

Epochs were averaged using MATLAB (v.7.01- The Mathworks, Inc, Natick, MA) to obtain ERPs for each participant in each experimental task. Grand averages were computed for each group and stimulus type in each experimental task. The N1 was measured as the most negative peak automatically detected in a time-window from 70 ms to 150 ms after stimulus onset. The P2 was measured as the most positive peak detected at the time-window from 150 ms to 250 ms. Amplitudes were measured relative to the mean voltage of each channel during the pre-stimulus baseline.

The ERPs were analyzed for the T7, FC5, CP5, and C3 electrodes (left hemisphere) and T8, FC6, CP6 and C4 electrodes (right hemisphere). These sites represented the left and right temporal lobes. It was documented that the temporal lobes are associated with the performance on dichotic listening (Hugdahl et al., 1999; Kimura, 1961a). Since the latencies and amplitudes for each hemisphere were very similar, and to avoid multiple comparisons, a region of interest (ROI) was created for the left and right hemispheres by calculating a mean measure of latency and amplitude using the four electrodes.

#### 2.5. Procedure

As a first step, all participants underwent cognitive and reading tests to determine their inclusion in the non-impaired readers group or dyslexic readers group. Next, the participants were seated comfortably inside a soundproof room and fitted with headphones. They were asked to look at a computer screen with a fixation cross. The experiment was divided into four blocks containing 100 trials, two blocks for the dichotic CV syllables task and two blocks for the dichotic vowels task. A 5-min break was given after each block.

In the dichotic CV syllables task, participants were instructed to press the right button of a joystick with their right middle finger if the target stimulus (/ka/) was presented in the right ear and to press the left button with their right index finger if the target stimulus was presented in the left ear. The same instructions were given for the dichotic vowels task, with the vowel /a/ as the target stimulus. Participants were instructed before each experimental block and received two training blocks containing 30 trials for each task before recording. A randomized sequence was administered for each participant.

### 3. Results

#### 3.1. Background measures

Independent t-tests were conducted to evaluate group differences for each of the background measures. No significant differences between the two groups were found for general ability (Raven) and attention (Symbol Search) measures. However, differences were found on the RAN, memory, phonology, and verbal fluency tests. Table 1 provides additional details. Table 2 shows the performance of each group on the reading measures. As the table illustrates, significant differences between the two groups emerged on most reading measures, with the dyslexic readers performing more poorly than the non-impaired readers.

#### 3.2. Dichotic target detection tasks

Accuracy and reaction time parameters were analyzed separately using repeated measures (RM) ANOVA, with group (dyslexic readers and non-impaired readers) as the between-subjects variable, and task (syllables and vowels) and ear (right and left) as the within-subjects variables. Bonferroni post-hoc test for pairwise comparisons was used as subsequent analysis. Thus, all reported p-values are corrected following Bonferroni correction. Only correct responses were analyzed for reaction time.

**Table 1**  
Cognitive background measures of the dyslexic and non-impaired readers.

Measure	Dyslexic readers group (N = 18)		Non-impaired readers group (N = 22)		t
	Mean	SD	Mean	SD	
Raven – accuracy	55.41	2.53	51.95	11.75	– 1.31
Raven – speed	1468.25	402.06	1480.00	600.71	.07
Symbol Search - accuracy <sup>a</sup>	10.24	1.92	11.24	1.87	1.62
Digit Span	9.00	3.30	11.52	2.80	2.64*
Working Memory-Opposites	-.81	.51	.09	.99	3.13**
RAN - script letters - time (sec)	32.18	10.85	21.24	2.59	– 4.06***
RAN - script letters - errors	.35	.78	.14	.36	– 1.02
RAN - objects - time (sec)	43.00	6.17	32.38	4.03	6.39***
RAN - objects - errors	.06	.24	.14	.48	-.66
Verbal Fluency	34.65	10.06	45.19	11.54	2.96**
Phonemic Deletion - accuracy	17.88	6.42	23.28	2.43	3.28**
Phonemic Deletion - time (sec)	185.76	78.73	100.00	21.52	– 4.36***

\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .

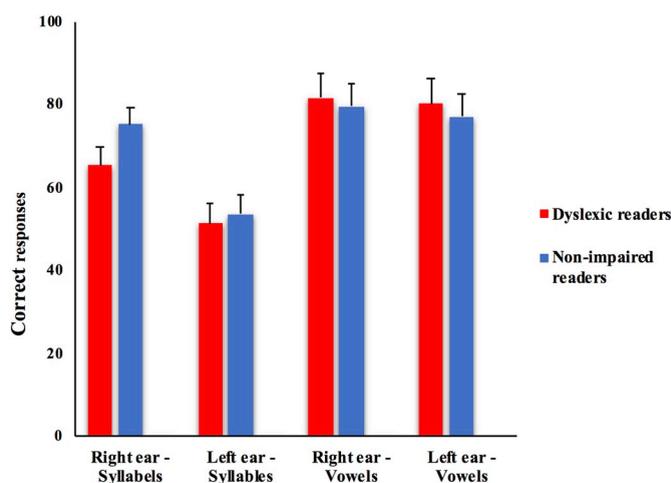
Accuracy scores for the Symbol Search, Digit Span, and Working Memory-Opposites tests are standard scores.

<sup>a</sup> The number of correct items completed in 120 s on the Symbol Search test.

**Table 2**  
Performance of the dyslexic and non-impaired readers on reading measures.

Measure	Dyslexic readers group (N = 18)		Non-impaired readers group (N = 22)		t
	Mean	SD	Mean	SD	
One-minute test for words total	66.06	17.58	119.09	13.70	10.45***
One-minute test for words -accuracy	63.53	17.88	118.81	13.49	10.86***
One-minute test for pseudowords - total	44.47	11.83	66.90	8.24	6.62***
One-minute test for pseudowords - accuracy	34.35	12.81	62.09	8.76	7.60***
Reading test - speed (sec)	.67	.24	.41	.05	– 4.55***
Reading test - errors	9.17	6.66	1.38	1.28	– 4.75**
Reading comprehension - time to answer 17 questions	507.23	173.07	377.43	131.74	– 2.62*
Reading comprehension - accuracy (out of 17)	10.59	2.15	10.33	1.79	-.39
Dictation - accuracy	7.82	5.90	1.00	1.05	– 4.71***
Parsing - speed (sec)	278.94	84.60	167.71	29.80	– 5.16***
Parsing – accuracy	43.35	4.91	44.90	2.53	1.26

\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .



**Fig. 1.** Mean accuracy for each reading group on the dichotic CV syllables and vowels target detection tasks. Error bars represent standard error of the mean.

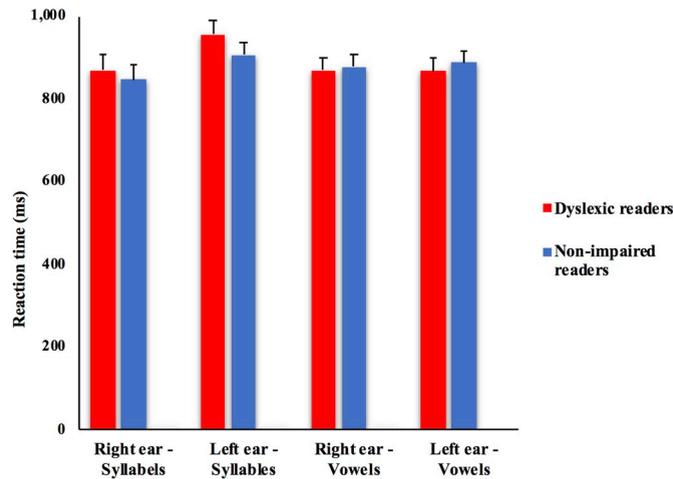


Fig. 2. Mean reaction time for each reading group on the dichotic CV syllables and vowels target detection tasks. Error bars represent standard error of the mean.

### 3.2.1. Accuracy parameters

Fig. 1 shows mean accuracy for the non-impaired and the dyslexic readers on the target detection tasks. A significant main effect of task was found, indicating higher rates of correct responses for the vowel target detection task compared to the syllables target detection task [ $F(1,34) = 50.05$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.60$ ]. In addition, a main effect of ear was evident, with greater accurate detections from the right ear, compared to the left ear [ $F(1,34) = 23.07$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.40$ ]. No significant main effect of group was found ( $p = 0.78$ ).

A significant interaction of task \* ear was found [ $F(1,34) = 26.90$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.44$ ], indicating higher rates of correct detections from the right ear compared to left ear on the dichotic syllables task [ $F(1,34) = 30.73$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.47$ ], while no significant difference was found between the ears for the dichotic vowels task ( $p = 0.25$ ). In addition, vowels produced higher hit rates compared to the syllables for both right [ $F(1,34) = 13.60$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.29$ ] and left [ $F(1,34) = 68.21$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.44$ ] ears.

The task \* group and ear \* group interactions were insignificant ( $p = 0.11$ ,  $0.30$ , respectively). The task \* ear \* group did not reach significance as well ( $p = 0.30$ ). However, simple effects analysis revealed that on the syllables task both groups showed higher hit rates for the right ear compared to the left ear, with a greater difference between the ears for the non-impaired readers [ $F(1,34) = 25.35$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.43$ ] compared to the dyslexic readers [ $F(1,34) = 8.61$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.20$ ]. No significant differences were found on the vowels task (non-impaired readers:  $p = 0.27$ ; dyslexics readers:  $p = 0.57$ ). Moreover, while the non-impaired readers showed no difference ( $p = 0.24$ ) between the accuracy parameters of the vowels and the syllables presented to the right ear, the dyslexic readers showed higher hit rates for the vowels compared to the syllables [ $F(1,34) = 15.09$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.31$ ]. For the targets presented to the left ear, both dyslexic [ $F(1,34) = 37.28$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.52$ ] and non-impaired readers [ $F(1,34) = 30.93$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.48$ ] demonstrated higher hit rates for the vowels compared to the syllables.

### 3.2.2. Reaction time parameters

Fig. 2 shows mean reaction times for the non-impaired and the dyslexic readers on the target detection tasks. The analysis revealed a main effect of ear [ $F(1,35) = 5.33$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.13$ ], with a shorter reaction time for the right ear target than the left ear target. No significant main effects were found for task ( $p = 0.28$ ) and group ( $p = 0.77$ ).

A significant interaction of task \* ear was found [ $F(1,35) = 9.80$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.22$ ]: on the dichotic syllables task, the reaction time for right ear was shorter compared to the left ear [ $F(1,35) = 11.21$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.24$ ]. No such difference was found for the left ear ( $p = 0.86$ ). In addition, the reaction time of vowels was shorter compared to the syllables presented to the left ear [ $F(1,35) = 7.14$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.17$ ]. No difference between the two stimuli was found for right ear targets ( $p = 0.49$ ).

The task \* group, and ear \* group interactions did not reach significance ( $p = 0.16$ ,  $0.83$ , respectively). The task \* ear \* group interaction was insignificant ( $p = 0.40$ ), however, subsequent simple effects tests revealed a greater difference between the ears in the dyslexic group [ $F(1,35) = 7.20$ ;  $p = 0.01$ ,  $\eta_p^2 = 0.17$ ] compared to the non-impaired group [ $F(1,35) = 4.12$ ;  $p = 0.05$ ,  $\eta_p^2 = 0.11$ ] on the syllables task. These differences were insignificant on the vowels task (dyslexic readers:  $p = 0.92$ ; non-impaired readers:  $p = 0.71$ ). Interestingly, the dyslexic readers showed longer reaction time for target syllable presented to the left ear compared to left ear target vowel [ $F(1,35) = 8.85$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.20$ ]. No such difference was found in the non-impaired readers ( $p = 0.50$ ). For the right ear target stimuli, no significant differences were found in the dyslexic readers ( $p = 0.98$ ) and the non-impaired readers ( $p = 0.30$ ).

### 3.2.3. Laterality index

Based on correct responses, a laterality index was calculated separately for the dichotic vowels and the dichotic syllables task by

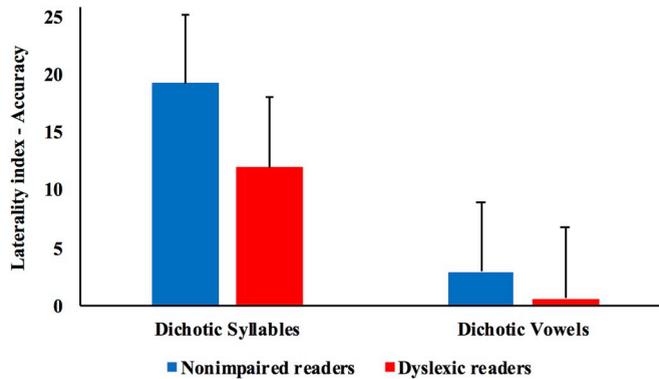


Fig. 3. Laterality index for the non-impaired and the dyslexic readers groups on each task.

using the equation  $\text{laterality index} = \frac{[\text{right ear correct} - \text{left ear correct}]}{[\text{right ear correct} + \text{left ear correct}]} * 100$ . The laterality index is positive for REA scores and negative for LEA ones (Eichele et al., 2005). Results of group (dyslexic readers and non-impaired readers) \* task (syllables and vowels) RM-ANOVA revealed a main effect of task, with a more leftward lateralization for the dichotic syllables than the dichotic vowels [ $F(1,38) = 28.77$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.43$ ]. No significant main effect of group was found ( $p = 0.20$ ). See Fig. 3.

### 3.3. Electrophysiological parameters

The amplitude and latency parameters of the N1 and P2 ERPs components were analyzed separately using a RM-ANOVA, with group (dyslexic readers and non-impaired readers) as the between-subjects variable, task (syllables and vowels) and ROI (right hemisphere and left hemisphere) as the within-subjects variables. Bonferroni post-hoc test for pairwise comparisons was used as subsequent analysis. Table 3 shows the amplitudes evoked on each hemisphere by the contralateral vowel/syllable target stimulus. See Table 4 for the latencies.

#### 3.3.1. N1 component

**3.3.1.1. Amplitude parameters.** The analysis of the N1 amplitudes revealed a significant main effect of ROI [ $F(1,29) = 5.92$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.17$ ], indicating enhanced amplitudes on the left hemisphere compared to the right hemisphere. The main effects of group and task were insignificant ( $p = 0.15$ ,  $0.89$ , respectively).

The ROI \* group interaction was insignificant ( $p = 0.96$ ). Simple effect tests indicated that the non-impaired readers showed a tendency for enhanced amplitudes in the left hemisphere compared to the right hemisphere [ $F(1,29) = 3.15$ ;  $p = 0.08$ ,  $\eta_p^2 = 0.10$ ]. The dyslexic readers showed no difference between the hemispheres ( $p = 0.10$ ). In addition, no differences between the groups emerged for the right and left hemispheres ( $p = 0.21$ ,  $0.22$ , respectively). The task \* group, task \* ROI, and task \* ROI \* group interactions were insignificant ( $p = 0.79$ ,  $0.84$ ,  $0.62$ , respectively).

**3.3.1.2. Latency parameters.** No significant main effects of task, ROI, and group were found ( $p = 0.67$ ,  $0.37$ ,  $0.80$ , respectively). The task \* group, ROI \* group, task \* ROI and task \* ROI \* group interactions were insignificant as well ( $p = 0.52$ ,  $0.38$ ,  $0.17$ ,  $0.77$ , respectively).

#### 3.3.2. P2 component

**3.3.2.1. Amplitude parameters.** The analysis of the P2 amplitudes revealed a main effect of group [ $F(1,37) = 4.45$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.11$ ], indicating enhanced amplitudes in the dyslexic readers compared to the non-impaired readers. In addition, a significant main effect of ROI was found [ $F(1,37) = 7.01$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.16$ ], with enhanced amplitudes on the right hemisphere compared to

Table 3

Means and standard deviations of the N1 and P2 amplitudes in each group.

ERP component	Task	Hemisphere (ROI)	Non-impaired readers	Dyslexic readers
N1	Dichotic syllables	Left	-6.96 (4.65)	-5.73 (4.01)
		Right	-5.79 (5.59)	-3.95 (3.01)
	Dichotic vowel	Left	-7.56 (3.54)	-5.50 (4.36)
		Right	-5.62 (4.46)	-4.06 (3.06)
P2	Dichotic syllables	Left	0.55 (3.82)	2.63 (5.57)
		Right	2.07 (3.81)	3.33 (4.28)
	Dichotic vowels	Left	-1.59 (4.79)	3.27 (4.76)
		Right	2.90 (4.27)	3.70 (7.21)

**Table 4**  
Means and standard deviations of the N1 and P2 latencies in each group.

ERP component	Task	Hemisphere (ROI)	Non-impaired readers	Dyslexic readers
N1	Dichotic syllables	Left	110.40 (19.35)	108.68 (22.37)
		Right	113.28 (21.24)	108.63 (19.06)
	Dichotic vowel	Left	109.73 (17.88)	113.91 (21.26)
		Right	106.70 (14.22)	104.89 (15.86)
P2	Dichotic syllables	Left	194.42 (26.24)	204.16 (29.54)
		Right	207.47 (30.70)	218.92 (38.63)
	Dichotic vowels	Left	190.25 (25.79)	196.58 (28.58)
		Right	194.42 (30.62)	195.31 (18.46)

the left hemisphere. The main effect of task was insignificant ( $p = 0.92$ ).

The interaction of task \* group was insignificant ( $p = 0.42$ ). Subsequent simple effect analysis indicated that on the vowels task, the dyslexic readers showed enhanced amplitudes compared to the non-impaired readers [ $F(1,37) = 4.26$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.10$ ]. No difference between the groups were found on the syllables task ( $p = 0.17$ ). Both groups showed no difference between the vowels and syllables (dyslexic readers:  $p = 0.64$ ; non-impaired readers:  $p = 0.49$ ). The ROI \* group and task \* ROI interactions were insignificant ( $p = 0.07, 0.26$ , respectively).

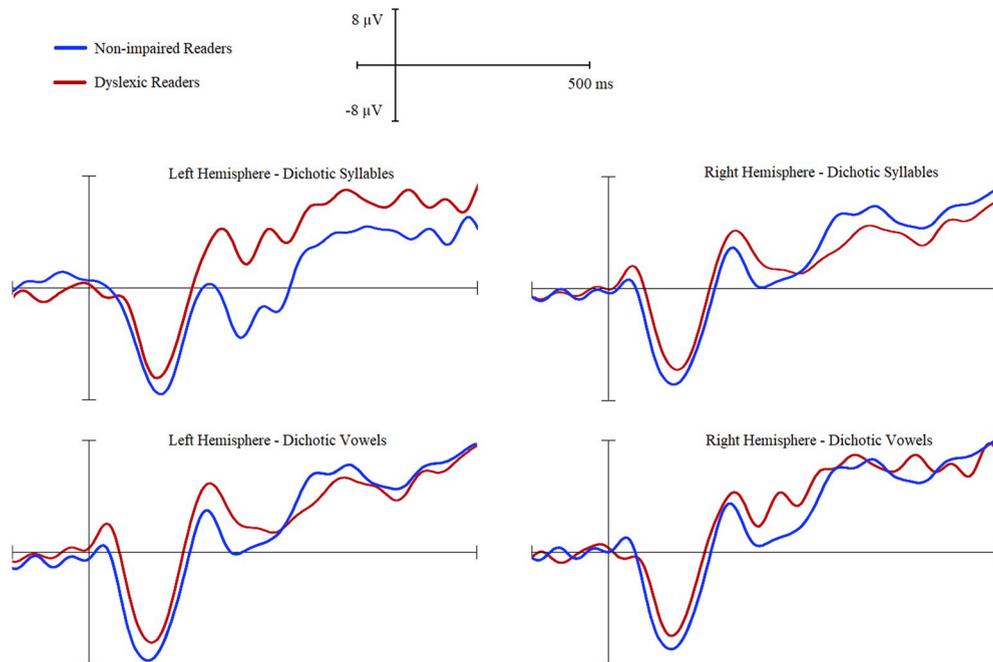
The task \* ROI \* group interaction was insignificant ( $p = 0.18$ ). Simple effect tests revealed that on the dichotic vowels task, the non-impaired readers showed enhanced amplitudes on the right hemisphere compared to the left hemisphere [ $F(1,37) = 11.31$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.23$ ]. No such difference was found for the dyslexic readers ( $p = 0.78$ ). For the syllables task, both groups showed no differences (dyslexic readers:  $p = 0.55$ ; non-impaired readers:  $p = 0.14$ ).

In addition, on the dichotic vowels task, the dyslexic readers showed higher amplitudes in the left hemisphere compared to the non-impaired readers [ $F(1,37) = 9.95$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.22$ ]. No such difference was found for the right hemisphere ( $p = 0.67$ ). For the dichotic syllables task, no differences between the groups emerged for the left ( $p = 0.17$ ) and right ( $p = 0.34$ ) hemispheres. Fig. 4 shows left and right hemispheres grand averages for the non-impaired and the dyslexic readers groups, according to task and contralateral target stimuli.

### 3.3.3. Latency parameters

The RM-ANOVA analysis for the P2 latency revealed a significant main effect of task [ $F(1,37) = 11.51$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.24$ ], the vowels produced shorter latencies than the syllables. The main effects of ROI and group were insignificant ( $p = 0.08, 0.24$ , respectively).

The task \* group interaction was insignificant ( $p = 0.33$ ). Simple effect analysis revealed that the dyslexic readers showed shorter



**Fig. 4.** ERPs grand averages in the non-impaired and dyslexic readers groups evoked by task (dichotic CV syllables and dichotic vowel) and contralateral target stimuli (left ear and right ear).

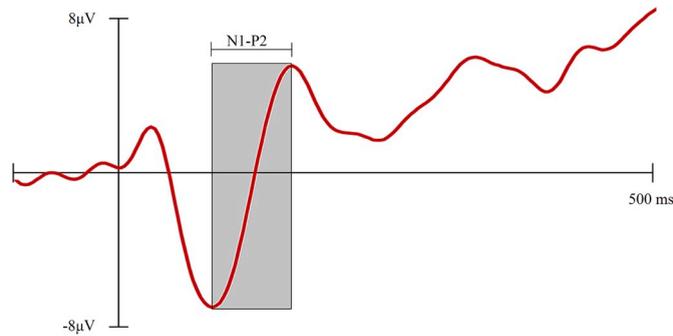


Fig. 5. An illustration of the N1–P2 complex.

latencies on the dichotic vowels task compared to the dichotic syllables task [ $F(1,37) = 8.47$ ;  $p < 0.01$ ,  $\eta_p^2 = 0.08$ ]. No such difference was found in the non-impaired readers group ( $p = 0.76$ ). In addition, no differences between the groups were found on the tasks (vowels:  $p = 0.55$ ; syllables:  $p = 0.19$ ). The ROI \* group and task \* ROI interactions were not significant ( $p = 0.83$ , 0.18, respectively).

The task \* ROI \* group interaction was insignificant ( $p = 0.70$ ). Simple effect analysis revealed that on the right hemisphere, the dyslexic readers showed longer latencies for the syllables compared to the vowels [ $F(1,37) = 6.60$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.15$ ]. No such difference was found in the non-impaired readers ( $p = 0.11$ ). For the left hemisphere, both groups showed no differences between the tasks (dyslexic readers:  $p = 0.36$ ; non-impaired readers:  $p = 0.56$ ).

### 3.3.4. N1–P2 ERPs complex

The N1–P2 complex was examined using peak-to-peak amplitude and time window parameters, see Fig. 5 for illustration. The amplitude and time window parameters were analyzed separately using a RM-ANOVA, with group (dyslexic readers and non-impaired readers) as the between-subjects variable, task (syllables and vowels) and ROI (right hemisphere and left hemisphere) as the within-subjects variables.

### 3.3.5. Amplitude parameters

No significant main effects of task, ROI, and group were found ( $p = 0.64$ , 0.35, 0.55, respectively). The task \* group, ROI \* group, task \* ROI and task \* ROI \* group interactions were insignificant as well ( $p = 0.61$ , 0.63, 0.06, 0.66, respectively). See Fig. 6.

### 3.3.6. Time window parameters

A main effect of ROI was found [ $F(1,33) = 6.14$ ;  $p < 0.05$ ,  $\eta_p^2 = 0.16$ ], indicating a shorter time window on the left hemisphere compared to the right hemisphere. In addition, the main effect of task almost reached significance [ $F(1,33) = 3.73$ ;  $p = 0.06$ ,  $\eta_p^2 = 0.10$ ], showing a tendency to a shorter time window for the vowels compared to the syllables. The main effect of group was insignificant ( $p = 0.34$ ). The interactions of task \* group, ROI \* group, task \* ROI, and task \* ROI \* group were insignificant ( $p = 0.51$ , 0.75, 0.71, 0.70, respectively). See Fig. 7.

### 3.3.7. Correlations between measures

Pearson correlation analyses were conducted to examine relevant relationships between dichotic target detection tasks and ERPs parameters, background measures with dichotic target detection, and background measures with ERPs. Calculations were performed

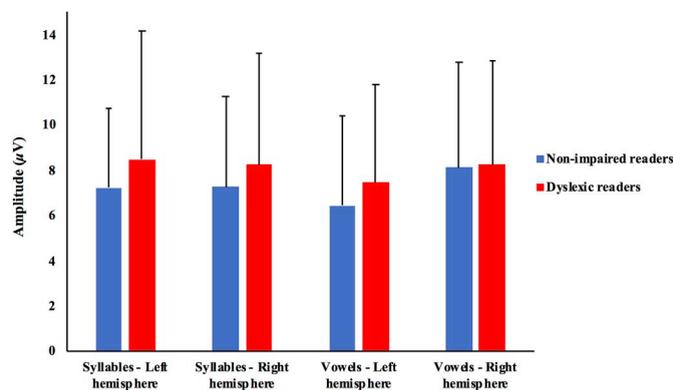


Fig. 6. Amplitudes of the N1–P2 complex for each reading group on the dichotic CV syllables and vowels target detection tasks. Error bars represent standard error of the mean.

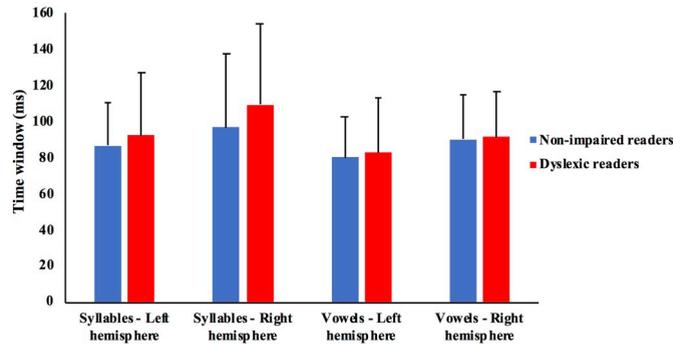


Fig. 7. Time windows of the N1–P2 complex for each reading group on the dichotic CV syllables and vowels target detection tasks. Error bars represent standard error of the mean.

separately for the non-impaired and dyslexic readers groups.

### 3.3.8. Dichotic target detection tasks and ERPs correlations

The non-impaired readers demonstrated a correlation between the accuracy parameters of the right and left ears on the dichotic CV syllables task ( $r = 0.59$ ,  $p < 0.01$ ). They also showed a correlation between the accuracy and reaction time for right ear CV syllable target ( $r = -0.59$ ,  $p < 0.01$ ). No significant correlations were found between these measures for the dyslexic readers.

The non-impaired readers also showed a correlation between the right ear accuracy parameters for syllables and vowels ( $r = 0.81$ ,  $p < 0.001$ ). The dyslexic readers showed a positive correlation between the two parameters as well ( $r = 0.67$ ,  $p < 0.05$ ). Using the Fisher  $r$ -to- $z$  transformation, no significant difference was found between these two correlation coefficients ( $p = 0.37$ ).

The dyslexic readers also showed a correlation between the amplitude of the P2 ERPs component in the right hemisphere evoked by the contralateral vowel target stimuli, and the accuracy parameter of the left ear vowel target stimuli ( $r = -0.60$ ,  $p < 0.05$ ). The non-impaired readers showed no significant correlation for these measures.

### 3.3.9. Background measures with dichotic target detection and ERPs

The non-impaired readers showed a correlation between the number of words read correctly on the *One Minute Test for Words*, and the reaction time for left ear target on the dichotic syllables task ( $r = -0.46$ ,  $p < 0.05$ ). No significant correlation was found for the dyslexic readers.

Among the dyslexic readers there was a relationship between the behavioral laterality index for CV syllables, and the accuracy parameter of the *Phonemic Deletion* test ( $r = -0.70$ ,  $p < 0.05$ ). No correlation was found for the non-impaired readers.

The non-impaired readers showed a correlation between the number of words read correctly on the *One Minute Test for Words* with the latency of P2 on the right hemisphere evoked by the left ear syllable ( $r = 0.44$ ,  $p < 0.05$ ). No significant correlation found for the dyslexic readers.

## 4. Discussion

The aim of this study was to investigate the functional speech lateralization in adult dyslexic readers. ERPs were recorded from non-impaired and dyslexic readers who performed dichotic CV syllables and dichotic vowels target detection tasks. The target detection paradigm was used to record reaction times and to avoid possible speech movement which may affect the EEG signals (Brooker & Donald, 1980; Szirtes & Vaughan, 1977). Based on the findings of previous studies (Helland & Asbjørnsen, 2001; Hugdahl et al., 1995; Shankweiler & Studdert-Kennedy, 1967; Studdert-Kennedy & Shankweiler, 1970), it was hypothesized that the dyslexic readers would show reduced functional asymmetry compared to the non-impaired readers for the dichotic CV syllables, and none of the groups would show functional asymmetry for the dichotic vowels.

Previous research suggests that dyslexic readers exhibit different patterns of ear advantage on DL tests than non-impaired readers (Helland, Asbjørnsen, Hushovd, & Hugdahl, 2008; Hugdahl et al., 1995; Kershner, 2016; Zurif & Carson, 1970), while variability across studies is well documented (Bryden, 1988b). In the present study, the behavioral results of the DL tasks showed a main effect of task, with higher accuracy scores for the dichotic vowels than the dichotic syllables. This finding is in line with earlier studies that compared CV syllables and pure tone processing in non-impaired and dyslexic adults (Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001; Sebastian & Yasin, 2008). This fact may suggest that the analysis of vowels is a more automatic process in non-impaired and dyslexic readers than the processing of syllables. In addition, the behavioral laterality index indicated that the two groups showed a left hemispheric specialization for dichotic syllables, and the dichotic vowels were more bilaterally presented. This result is in line with the findings of Studdert-Kennedy and Shankweiler (1970) who found NEA for dichotic vowels and a REA for consonant-vowel-consonant syllables in non-impaired readers.

The behavioral findings described above suggest that the two groups in the current study had a left hemispheric specialization for dichotic CV syllables. Considering the NEA that emerged in Brunswick and Rippon's (1994) study of dyslexic children, it is suggested that the adult dyslexic readers in the current study may have developed compensatory processes through time.

However, the comparison between the right ear and left ear in each group showed that non-impaired readers had a greater REA for syllables than the dyslexic readers, with NEA for vowels in both groups. Moreover, the fact that the non-impaired group showed a negative correlation between accuracy and the reaction time of the right ear target on the dichotic syllables task may emphasize the effectiveness of the left hemisphere in this group compared to the left hemisphere in the dyslexic readers. Furthermore, the significant correlation found between the accuracy of the right ear and left ear targets may suggest a more established collaboration of the hemispheres in the non-impaired readers. No such significant correlations were found for the dyslexic readers group.

In addition to the accuracy parameters which may point for a reduced REA in the dyslexic readers group, the non-impaired readers had shorter reaction times for both ears than the dyslexic readers, when dichotic CV syllables were presented. Furthermore, the significant negative correlation found between the behavioral laterality index and phonology processing in the dyslexic group could strengthen the assumption of a reduced hemispheric specialization for speech in adult dyslexics. Hence, the results of the current study may accord with previous studies establishing the reduced efficiency of the left hemisphere in dyslexics (Cohen et al., 1992; Helland & Asbjørnsen, 2001; Hugdahl et al., 1995).

The N1–P2 ERPs evoked by the DL tasks yielded between and within group differences as well as main effects. Eichele et al. (2005) found a shorter latency for N1-AEPs in the left hemisphere than in the right hemisphere in non-impaired readers, with no amplitude differences between the sites. The N1 is sensitive to the spectral-temporal features of the onset of a stimulus. In addition, several temporally overlapping components contribute to the waveform. Finally, the lateral contribution to the N1 has been found to be generated on lateral aspects of the temporal lobes (Näätänen & Picton, 1987; Picton et al., 1999). In the current study, no significant N1 latency differences were evident between or within the groups. However, a main effect of ROI did emerge for the N1 amplitudes, with an overall enhanced activation on the left hemisphere. Additional analysis revealed a tendency for greater activation of the left hemisphere in the non-impaired readers. While Brunswick and Rippon (1994) found significantly greater N100 amplitudes for the left temporal region in non-impaired children compared to dyslexic readers during CV syllable DL, the results of the N1 in the current study might reflect a compensatory mechanism that the dyslexic readers developed over time.

Previous research also found impaired attention in dyslexic readers during the performance on various experimental tasks (Facoetti et al., 2010; Ruffino et al., 2010; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014). The N1 component is considered to reflect the encoding of the physical properties of the auditory stimulus (Moiescu-Yiflach & Pratt, 2005) and may reflect attentional resources (Papageorgiou et al., 2009; Schwent & Hillyard, 1975). Taken together, the results may suggest that the adult dyslexic readers have learned with time to allocate the required attentional resources for the initial stage of processing.

An interesting finding in the present study was the main effect of group found for the P2 amplitudes, with dyslexics showing greater amplitudes compared to non-impaired readers. The P2 is a positive peak following the auditory N1 and may reflect a late selection (McPherson, 1996). The fact that the dyslexic readers were required to exert greater effort than the non-impaired readers may point to a developmental cognitive deficit persisting into adulthood, despite any remediation and training they may have received. Additionally, the dyslexic readers showed enhanced amplitudes on the left hemisphere evoked by right ear target stimuli, compared to the non-impaired readers. This finding may suggest that although the N1 patterns may reflect compensation for the dyslexics, a later process is still deficient in this group.

The enhanced P2 amplitudes on the left hemisphere found in the dyslexic readers may accord with the studies demonstrating the greater activation of the left hemisphere in dyslexic children compared to non-impaired children during auditory phonological tasks. These studies found greater evidence of lactate (a marker of increased glucose metabolism) in left cerebral anterior regions in the dyslexic group. Researchers suggested that the task required greater mental effort from the dyslexics than the non-impaired children (Richards et al., 1999, 2000). The verbal efficiency theory (Perfetti, 1985), which claims that poor readers must exert more mental effort than non-impaired readers in order to accomplish the same task, may be one explanation for the higher amplitudes found among dyslexics. According to Kimura (1967) each ear has greater neural representation in the contralateral hemisphere than the ipsilateral one. The negative correlation between the right hemisphere's P2 amplitude evoked by the contralateral vowel target stimuli may suggest that dyslexics have a differently organized auditory system than non-impaired readers.

Whereas increased P2 amplitudes may reflect attentional capture (Kanske, Plitschka, & Kotz, 2011), another explanation in regard to the enhanced activation in the dyslexic readers group can be related to the findings of Arciuli, Rankine, and Monaghan (2010). The authors examined whether a relationship between DL performance and reading ability could be observed in non-impaired children and adults. They found that the extent to which participants could overcome the preference to respond to the right ear when listening to short-long pairs was a predictor of reading accuracy and comprehension. In addition, the ability to overcome the preferences to respond to the left ear when listening to long-short pairs was predictive of higher reading comprehension. The authors concluded that participants who were able to exert top-down control over the stimulus-driven preference to respond to long voice onset time (VOT) syllables were better readers. These findings may suggest that dyslexic readers may lack the ability to activate sufficient top-down control, a factor which may affect their reading abilities. It should be noted that the current study did not apply attentional manipulations during the experimental blocks. Future research can address this issue more carefully by combining DL and ERPs techniques, using forced attention paradigms (Hugdahl & Andersson, 1986).

In addition to amplitude differences, a main effect of stimuli was found, with a shorter latency for the dichotic vowels than the dichotic syllables. This finding accords with the behavioral accuracy scores the groups achieved on the dichotic vowels and dichotic syllables tests, and may support the contention that the processing of vowels is a more automatic process in non-impaired and dyslexic adults than the processing of syllables. However, the fact that the dyslexics showed a later P2 for syllables than vowels on the right hemisphere might imply that hemisphere functions in a less efficient manner than it does in non-impaired readers.

DL studies mainly represent behavioral experiments which are rarely analyzed by electrophysiological methodologies (Bayazit, Oniz, Hahn, Güntürkün, & Özgören, 2009). Using brain imaging techniques with dichotic presentations of CV syllables stimuli, the DL

performance of non-impaired participants has been linked to left hemisphere dominance (Bethmann, Tempelmann, Bleser, Scheich, & Brechmann, 2007; Hugdahl et al., 1999; Van den Noort, Specht, Rimol, Erslund, & Hugdahl, 2008). Behavioral studies with dichotic presentation of vowels found NEA in non-impaired participants (Shankweiler & Studdert-Kennedy, 1967; Studdert-Kennedy & Shankweiler, 1970). Nonetheless, both groups in the current study showed enhanced activation on the right hemisphere compared to the left hemisphere when it came to the P2 component. This finding is consistent with several former studies which used DL technique with speech stimuli. For example, using ERPs and DL including speech stimuli, Bayazit and colleagues found higher activation on the right hemisphere for the N1–P2 time window (Bayazit et al., 2009). Using functional magnetic resonance imaging and DL, Pollmann, Lepsien, Hugdahl, and Yves von Cramon (2004) found that both right and left ear target detections elicited a right hemisphere activation. According to these authors, decisions on target presence in dichotic stimuli may be predominantly processed in the right posterior orbital gyrus. Hence, the right lateralization found for the P2 amplitudes may be a consequence of the target detection paradigm employed on the current study. This finding can be further investigated in future similar studies.

In the present study, two basic kind of auditory speech stimuli were presented, syllables and vowels. The results of the reported study may accord with the findings of Vandermosten et al. (2010), who used categorization tasks to compare the performance of non-impaired and adult dyslexic readers. Their design included four stimulus continua based on two measurements, speech versus nonspeech and temporal (rapidly changing acoustic cues) versus nontemporal (steady-state). It was found that the dyslexic readers were specifically impaired at categorizing speech and nonspeech sounds that differed in terms of rapidly changing acoustic cues. No differences between the groups were found for steady-state speech and nonspeech sounds. The authors concluded that dyslexic readers are characterized by an auditory temporal processing deficit that is not speech-specific. It was suggested that dyslexic readers do not use a distinct neural mechanism for processing temporal versus steady-state sounds. In regard to the conclusions of their study, Electrophysiological studies may support this view. It was suggested that dyslexic readers do not present the typical left hemispheric dominance in response to speech or rapidly changing signals (Lyytinen et al., 2005). The behavioral results of the present study may also support this view since the adult dyslexic readers showed different hemispheric specialization patterns for syllables and vowels, as compared to the non-impaired readers.

In conclusion, the results of this study suggest that adult dyslexic readers and adult non-impaired readers differ in their functional lateralization of speech. The N1–P2 ERPs complex in the dyslexic readers group, as well as their performance on the DL tasks, supports the notion that developmental dyslexia is linked to altered cerebral lateralization for speech. The findings of the current study may extend previous data showing altered hemispheric specialization for speech in dyslexic readers (Brunswick & Rippon, 1994; Heim et al., 2003; Helland & Asbjørnsen, 2001; Illingworth & Bishop, 2009).

With regard to limitations, it is important to note that this study used a non-forced paradigm. Additional research including the forced-attention paradigm in DL (Hugdahl & Andersson, 1986) might add insights about the functional lateralization for speech in adult dyslexic readers. Given that the N1–P2 complex might be related to attentional resources (McPherson, 1996; Schwent & Hillyard, 1975) and the auditory lateralization might be influenced by forced-attention paradigms (Bryden, Munhall, & Allard, 1983; Hugdahl et al., 2000), such research may add to our knowledge about the relationship between functional speech lateralization and attentional modifications in adult dyslexic readers. Future research can also address compensation and functional lateralization for speech in adult dyslexic readers in relation to the type of stimuli. Earlier research found different patterns of speech lateralization in dyslexic children for CV syllables, digits, and words (Moncrieff & Black, 2008). Nevertheless, this study adds to our knowledge in the field of hemispheric specialization for speech in dyslexic readers.

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