Altered hemispheric asymmetry during word processing in dyslexic children: an event-related potential study

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The present event-related potential study aimed at finding neurophysiological correlates of inadequate reading performances in developmental dyslexia. By using the same set of words in different linguistic tasks, we found variations of cortical asymmetry between dyslexic individuals and controls starting with the N420, a component supposed to index the phonological processing during reading. Whereas in controls this component was left lateralized, in disabled readers it was more distributed across hemispheres. The observed lack of lateralization in dyslexic individuals was also found in the later slow negative wave that developed in the 700 to 1500-ms time interval. We postulate that the altered asymmetry is related to an impairment of the grapheme–phoneme conversion mechanism. The findings would therefore support the hypothesis of a phonological deficit underlying this learning disability. *NeuroReport* 17:429–433 © 2006 Lippincott Williams & Wilkins.

Keywords: children, dyslexia, event-related potentials, evoked potentials, hemispherical asymmetry, lateralization, N400-like, phonological processing, reading, word processing

Introduction

Developmental dyslexia is a specific and significant impairment in reading abilities, not explained by any kind of deficit in general intelligence, learning opportunity, motivation or sensory acuity [1]. Many studies have provided considerable evidence that the main mechanism leading to children's reading disabilities is specifically linguistic, namely phonological in nature [2–6]. This impaired mechanism is supposed to involve a deficit of 'phonological awareness', that is, the awareness that spoken words can be decomposed into their phonological constituents, represented by the alphabetic characters in the written language [2]. Specifically, dyslexic individuals seem to have a basic defect of direct access to, and manipulation of, phonemic units. As a consequence, they show a general impairment in all those subprocesses involved in the grapheme–phoneme conversion: the segmentation of words into their constitutive graphemes, the mapping between these graphemes and their corresponding phonemes, and the final assemblage of phonemes in the whole sound of the word. This defect leads dyslexic individuals to very inadequate reading performances, especially during new or unfamiliar word decoding.

Several neuroimaging studies have related phonological processes to a broad cortical network that includes temporal (i.e. fusiform gyrus, superior and middle temporal gyri, planum temporale), inferior parietal (i.e. angular gyrus and supramarginal gyrus) and perisylvian frontal (i.e. Broca's area) regions [7]. Although previous studies did not adequately distinguish the different subprocesses involved in phonological elaboration [8], data provided converging evidence that, in the left hemisphere, posterior areas are involved in phonological awareness, grapheme–phoneme mapping, storage and retrieval of phonological information, whereas anterior areas are involved in segmentation, assembling and word production [9,10]. With regard to electrophysiological correlates, a negative wave, peaking shortly after 300 ms from the stimulus onset and located over the left temporal cortex, seems to be the most robust finding associated with phonetic transformations performed on pronounceable orthographic patterns by adult readers [11]. Using a similar task in a developmental event-related potential study, Grossi *et al.* [12] found a comparable negative component, with a very similar spatial distribution, which was delayed, in youngest readers, of about 100 ms: a result in line with the hypothesis of an increased latency for most event-related potential cognitive components in children. With reference to neurophysiological correlates of dyslexia, several studies have shown reduced hemispheric asymmetry, particularly at the level of temporal lobe structures, in both children and adults [13–16]. The attempt to relate this altered hemispheric lateralization to a specific phonological disability by using words as more ecological stimuli and manipulating only the task, instead of the stimulus set, however, is still missing.

The current event-related potential research aimed at examining possible neurophysiological differences between dyslexic children and non-impaired readers during written word processing. According to the phonological deficit hypothesis of dyslexia, we expected to find an altered hemispheric lateralization of disabled readers specifically during phonological processing compared with different linguistic elaborations of the same set of words. The rationale underlying this research is that the same sample of stimuli is able to activate distinct cortical networks only according to the task requirements [17], overcoming, in this way, the methodological limits of prior studies that used, for different tasks, a different set of linguistic stimuli.

Materials and methods

Participants

Fifteen native Italian-speaking children (11 boys; 8–14 years) entered the research after the informed consent of their parents. They had an average handedness of 87% on the Edinburgh Inventory [18], and normal or corrected-to-normal vision. The clinical sample consisted of eight children with developmental dyslexia (six boys; mean age: 9.87 years, ±1.87 SD). They were recruited from the Children's Neuropsychiatric Medical Facility of San Donà di Piave, and were diagnosed as phonological dyslexic individuals on the basis of normal IQ [19] and inadequate performances on specific batteries for reading evaluation (mean reading times: 1.33 syllable/s) [20,21]. Children with associated attention deficit disorder with hyperactivity were excluded from the experiment. Seven children (five boys), matched for age (mean: 10.21 years, ±1.58 SD) and IQ, and showing normal reading performances, served as the control group.

Materials and procedure

For each task, stimuli consisted of 80 visually presented word pairs, to which a judgement was required. In the *phonological* task, aimed at testing the phonological deficit hypothesis of dyslexia, children were asked to perform a rhyme matching between the words of each pair, by pressing a yes/no button with the left hand. In two other additional tasks, used to test possible differences between groups during both a low level and a high level linguistic process, children were asked to perform a visual word matching (*orthographic* task), and a meaning word matching (*semantic* task), respectively. Stimuli of each pair were all disyllabic Italian words with an average frequency of usage [22]. Further, the same 80 words were used in all tasks as the first stimulus of the pairs, to be sure that the possible effects could be attributed only to the processes induced by the task, and not to the elaboration of confounding features related to the stimuli. Participants were seated in front of a computer screen, in which word pairs were displayed word by word. The first stimulus (W1) appeared in the centre of the screen for 1500 ms; followed, after 2000 ms of inter-stimulus interval, by the second stimulus, which was visible until the child pressed a button, but no longer than 5000 ms; the intertrial interval was 3000 ms. The experimental session included three blocks, each corresponding to one task.

Electroencephalography data acquisition and analysis

Children's behavioural performances were measured by means of judgement reaction times and error rates; whereas the electrophysiological data were measured in terms of the components (mean amplitude values) evoked by the first word of each pair. Electroencephalography was continuously collected in DC mode, with a low-pass filter set to 30 Hz and a sampling rate of 500 Hz. Brain electrical signals were recorded by means of 38 tin electrodes [23] referred to Cz and converted offline to average reference. The continuous signal was epoched in 13-s intervals around W1, and corrected for eye movements by means of the Brain Electrical Source Analysis package [24]. Trials with residual artefacts (exceeding 100 μV) in the shortened epochs (from 500 ms before to 4500 ms after W1 onset) were visually inspected and rejected. The accepted epochs (about 54%) were averaged for each participant and for each task. For statistical analysis, two time intervals were selected, according to both a priori knowledge of the literature [11], with adjustments due to latency differences between children and adult populations, and to visual inspection of the waveforms: 370–470 ms (corresponding to the N420) and 700–1500 ms (corresponding to the slow negative wave) after W1 presentation. Within these time windows, we selected six groups of electrodes by means of the orthogonal variation of two factors: caudality (anterior–posterior gradient) and laterality (left–right gradient). We tried to include in the analysis as many locations as possible, but, at the same time, we excluded the most external and noisy electrodes. As shown in Fig. 1, we included the following clusters: anterior–left group (F3, F7, FC3, C3), anterior–central group (Nz, FPz, Fz, FCz), anterior–right group (F4, F8, FC4, C4), posterior–left group (P3, P7, TP7, O1), posterior–central group (Cz, CPz, Pz, Oz) and posterior–right group (P4, P8, TP8, O2). We performed a mixed analysis of variance (ANOVA) with the following factors: group (control vs. dyslexic individuals), task (orthographic vs. phonological vs. semantic), caudality (anterior vs. posterior) and laterality (left vs. central vs. right). For all the results reported, the Huynh–Feldt correction was applied where sphericity assumptions were violated [25]; in these cases, the uncorrected degrees of freedom, epsilon values and the corrected probability levels are reported. With regard to behavioural measures, we performed a similar ANOVA, using the factors group and task. Post-hoc comparisons were computed using Newman–Keuls tests, settled with $P<0.05$.

Results

Behavioural data revealed slower reaction times in dyslexic individuals than in controls [mean: 2253 vs. 1656 ms; group: F(1,13)=8.95, $P<0.01$]. In both groups, reaction times were longer for semantic (mean: 2266 ms) than for phonological and orthographic tasks [1788 and 1810 ms, respectively; task: F(2,26)=23.06, $P<0.001$]. The pattern of these two main effects was mirrored in the significant interaction group-task [F(2,26)=3.33, $P<0.05$]. Furthermore, error rates showed that dyslexic individuals performed worse than controls in all tasks [group × task: F(2,26)=3.39, $P<0.05$], although the difference reached significance in post-hoc analyses only during the phonological task (mean: 13.13% for dyslexic individuals, 2.68% for controls).

Figure 1 shows groups' grand mean waveforms across all tasks. The first marked difference between groups was clearly evident starting 300 ms after W1 presentation. This difference persisted up to around 500–600 ms and was more localized over anterior left sites, where controls showed a broader negative peak than dyslexic individuals. The second largest difference was evident as a slow negative wave started around 700 ms after W1 onset and lasted until its offset. Namely, whereas controls were relatively more negative than dyslexic individuals in posterior sites, mainly in the left hemisphere, dyslexic individuals were relatively more negative in the midline, mainly at anterior sites. The intervals selected for statistical analysis were based on the literature and on these differences found in the waveforms.

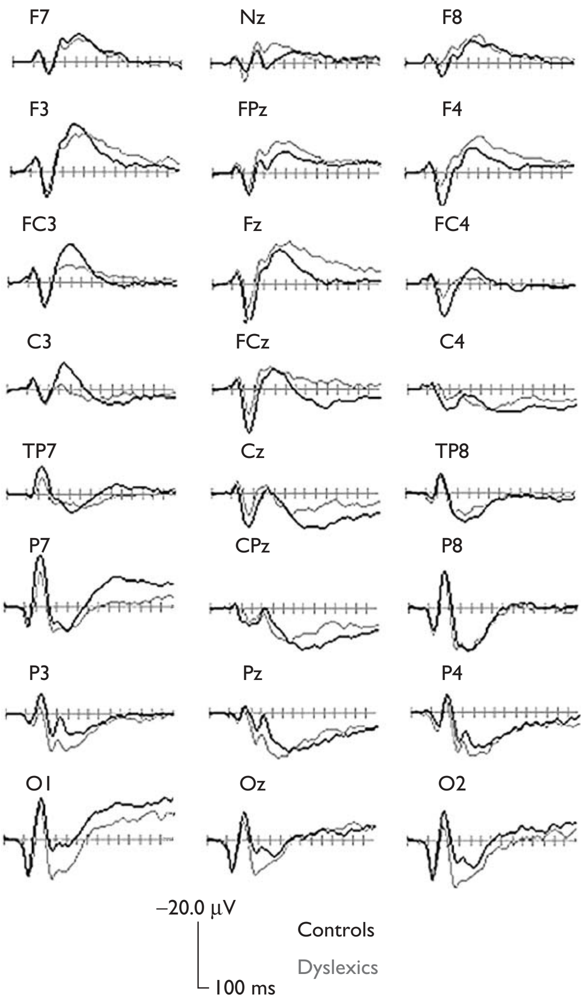

Fig. 1 Grand mean waveforms of each group are shown for the electrodes that entered the analyses (factor task collapsed) in a time interval of 1500 ms after the stimulus onset (baseline: 100 ms).

In the first analysed interval (i.e. 370–470 ms after W1 onset), we found a significant group × caudality × laterality three-way interaction [F(2,26)=3.68, ε=0.9, $P<0.05$; see Fig. 2a].

The main differences between groups were found at anterior cortical regions. Controls were clearly left lateralized, as they showed a significantly greater negativity in the left cluster than in the central ($P<0.001$) and right clusters ($P<0.001$). Dyslexic individuals, instead, exhibited a lack of lateralization in the same anterior area, with a greater negativity over the central sites than the right sites ($P<0.05$). With regard to between-group differences, we found a significantly greater negativity of controls than dyslexic individuals over left anterior locations ($P<0.01$). In posterior areas, instead, control and dyslexic children showed a quite similar pattern across hemispheres. Nevertheless, post-hoc tests showed a significant lateralization in controls, with right sites significantly more positive than both central and left sites ($P<0.001$ and $P<0.01$, respectively); instead, dyslexic individuals did not exhibit amplitude differences along the left–right axes.

In the second interval, 700–1500 ms after W1 onset, ANOVA revealed a significant group × laterality interaction [F(2,26)=4.12, ε=1, $P<0.05$]. Controls were left lateralized also in this time interval (Fig. 2b), showing a significant greater negativity over left clusters than both right and central clusters ($P<0.05$ and $P<0.001$, respectively). Dyslexic individuals, on the contrary, showed again a lack of lateralization and a more distributed activity, significantly different from controls' activation only at central sites ($P<0.05$). In this interval, we also found the task × caudality × laterality interaction significant [F(4,52)=3.23, $P<0.05$], which was revealed as tasks differed only in the posterior central cluster, with the orthographic task significantly more positive than the other two tasks, and the

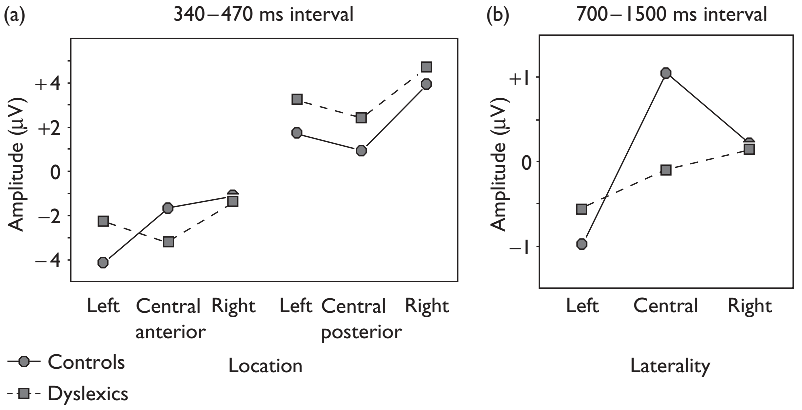

Fig. 2 Graphs representing the significant interactions of the factors: (a) group, caudality and laterality in the 340 to 470-ms interval and (b) group and laterality in the 700 to 1500-ms interval.

semantic task significantly more negative. On the basis of both our hypothesis that different tasks should activate specific cortical networks, and the fact that unimpaired children in this interval are expected to begin task-specific processes, we repeated such a statistical analysis for the control group alone to disentangle the effects of these processes from group effects. We found again a significant task × caudality × laterality interaction [$F(4,24)=2.82$, $P<0.05$]. In the post-hoc tests, the semantic task showed, at posterior sites, a reduced left–centre difference (that is negativity of left compared with central sites) and therefore was less left lateralized with respect to the other two tasks.

Discussion

The present event-related potential study clearly demonstrated the presence of an altered hemispheric lateralization in dyslexic individuals during linguistic processing [13–16] and supports the hypothesis of a specific disability in manipulating the phonological features of letter strings [7]. Indeed, we found differences of cortical asymmetry between dyslexic individuals and controls at the level of a specific event-related potential component, supposed to index the phonological elaboration during reading [11,12]. Such a component, detected in the first time window, the N420, showed an altered hemispheric lateralization in disabled readers compared with controls: whereas the latter exhibited a significant left anterior lateralization, the former exhibited an N420 more distributed along the left–right axes. This pattern was maintained by each group also over posterior areas, although the component shifted overall to positive amplitude values. A component similar to our N420 has been described, with small age-related differences of latency, both in non-impaired children of different age [12] and in adults [11]. These studies attributed this component to the phonological processes required by rhyme detection tasks. In particular, the authors related it to the phonetic transformation performed on pronounceable orthographic patterns, after the initiation of grapheme analysis [11] or, more generically, to the left hemisphere specialization for phonological decoding [12]. We interpret our N420 in a slightly different way by suggesting that it might be related to phoneme extraction and assemblage stages of the grapheme–phoneme conversion during word reading. Compared with the previous studies, we argue in favour of a more low-level interpretation, on the basis of two main reasons. First, we found the N420 not only in the phonological, but also in the semantic and orthographic tasks, a result that suggests a common early stage of linguistic processing preceding, or unrelated to, the specific task demands. Second, mean reading times, in normal readers with the age of the present sample, are estimated from the literature to be about 3.0 syllable/s [21]; therefore, during the N420 interval, children were still engaged in the basic process of word decoding. This supports the view that, at this time, the execution of a more high-level linguistic processing was very unlikely. According to the phonological deficit hypothesis, the lateralization differences we found between groups suggest that dyslexic individuals' performances in linguistic tasks (from the simple reading to the semantic judgement) are delayed because of a failure of some early subprocesses of print to sound conversion.

Furthermore, in the later slow negative wave measured in the 700- to 1500-ms interval, we found a lack of asymmetry in dyslexic individuals compared with the significant left lateralization of controls. We consider this time window functionally different from the earlier one, because in this interval the two groups were likely engaged in different cognitive processes. In fact, normative data on reading times suggest that, in this time window, non-impaired readers have just finished reading the word, whereas dyslexic individuals would be engaged in the decoding process throughout the whole W1 presentation interval. Therefore, the observed lateralization pattern in controls was not related to the grapheme–phoneme conversion, but rather to later task-related processes. The significant three-way interaction task × caudality × laterality found only in the control group supports the interpretation of the existence of task-specific processes, at this level of linguistic elaboration, only for normal readers. On the contrary, in the same time window, dyslexic individuals were still completing the word reading; therefore, their lack of lateralization in this interval, as in the previous one, is probably associated with defective mechanisms of the grapheme–phoneme conversion process.

Conclusions

The present event-related potential data point to a reduced hemispheric lateralization of dyslexic children during written word processing. This decreased cortical asymmetry seems to be specifically related to the grapheme–phoneme conversion process that, in non-impaired readers, starts in left posterior regions and terminates, with the phonemic assembling, in left anterior perisylvian areas. The present finding supports the hypothesis of a phonological deficit underlying this developmental disability.

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