

Delta EEG activity as a marker of dysfunctional linguistic processing in developmental dyslexia

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Abstract

The present study used delta EEG band to test the hypothesis of a cerebral maturational delay and a functional altered cerebral asymmetry for phonological processing in dyslexic children. A group of 14 children with dyslexia and 28 matched controls participated in a linguistic paradigm in which the same words were processed in three tasks: phonological, semantic, and orthographic. Delta amplitude was computed as an index of cortical inhibition in four different phases of word processing. In anterior sites, controls showed left activation (reduced delta) during the phonological task and bilateral activation in the other two tasks. Conversely, children with dyslexia showed greater overall delta amplitude, indexing a cerebral maturation delay and an altered language laterality pattern. In the phonological task they had larger left anterior delta (inhibition of left frontal linguistic locations) and smaller left posterior delta amplitude (activation of left posterior sites silent in controls). Results support the phonological deficit hypothesis of developmental dyslexia and the validity of EEG delta band as functional and clinical measure of language laterality.

Descriptors: Dyslexia, Delta band, Cerebral maturation, Phonology, Semantics, Lateralization

Developmental dyslexia is the most frequent specific learning disability in childhood and consists of a pronounced and persistent difficulty in learning to read, despite normal intelligence, perception, motivation, and adequate educational and socioeconomic opportunities (World Health Organization, 1993). Although sensory and attentional abnormalities have been often reported in people with dyslexia (Farmer & Klein, 1995; Stein & Walsh, 1997; Tallal, 1980), there is converging evidence that the main impaired mechanism involved in their reading disabilities is linguistic in nature, more precisely, phonological (Ramus, 2003; Shaywitz, 1998; Shaywitz & Shaywitz, 2005; Temple et al., 2001). Indeed, because sensorimotor symptoms are present only in a subsample of dyslexic children, whereas phonological impairments are always present, recent studies have found that the most revealing sign of dyslexia is a specific phonological deficit, which sometimes co-occurs with a more general sensorimotor syndrome (Ramus, 2003, 2004; Ramus et al., 2003). More specifically, dyslexic children suffer from a deficit of phonological awareness, that is, from difficulties primarily in understanding the relationships between the graphemes of the written word and

the corresponding phonemes of the spoken word, and a secondary difficulty in the manipulation of sublexical units in verbal working memory (Frith, 1985). As a direct consequence, people with dyslexia show a general impairment in all those subprocesses involved in the grapheme–phoneme conversion, resulting in a highly inadequate reading performance, as well as other, more or less closely associated, linguistic deficits, that is, spelling, writing, and spoken language (Ramus, 2003, 2004; Ramus et al., 2003). Concerning the neurobiological correlates of dyslexia, a considerable amount of data has highlighted structural and functional abnormalities in a broad cortical network, mainly distributed in the left hemisphere (for a review, see Démonet, Taylor, & Chaix, 2004) and usually involved in phonological processing (Price, 1998), which includes perisylvian and temporo-parieto-occipital brain areas (i.e., Broca's area, planum temporale, superior and middle temporal gyri, fusiform gyrus, angular gyrus, and supramarginal gyrus). In particular, many functional brain-imaging studies have shown an impairment of the left posterior brain system, that is, the disruption of the connections between dorsal and ventral routes for reading (Démonet et al., 2004; Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; Paulesu et al., 2001; Simos, Breier, Fletcher, Bergman, & Papanicolaou, 2000; Temple et al., 2001). As a consequence, whereas in normal readers the neural activity related to reading spreads from posterior toward anterior brain regions of the left hemisphere, in people suffering from dyslexia increased activation in either the frontal left- or right-sided regions (or both) has been interpreted as an attempt to overcome failure of left posterior areas (Démonet et al., 2004; Georgiewa et al., 2002; Shaywitz et al., 1998; Simos et al., 2000).

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Studies aimed at discovering the specific relationship between electroencephalogram (EEG) brain activity and developmental dyslexia have found, under a resting condition, an overall increase in slower rhythms (i.e., delta and theta bands) and a decrease in faster waves (especially alpha) in children with reading disabilities (whether associated or not with other learning disorders; Ahn et al., 1980; Colon, Notermans, DeWeerd, & Kap, 1979; Fonseca, Tedrus, Chiodi, Cerqueira, & Tonelotto, 2006; González-Garrido et al., 1993; Harmony, Hinojosa, et al., 1990; John et al., 1983; Sklar, Hanley, & Simmons, 1972). Fewer studies found no electrophysiological differences between impaired and normal readers in the resting condition (Fein et al., 1986; Yingling, Galin, Fein, Peltzman, & Davenport, 1986). This lack of complete consistency across studies might be explained by confounding variables related to sample selection (e.g., few participants, phenotypic variability, comorbidity) and by the use of substantially different experimental settings (parameters of EEG recording and analysis). The pattern of increased slower rhythms and decreased faster waves typically marks infancy and early childhood and gradually tends to become inverted over age (Gasser, Verleger, Bacher, & Sroka, 1988; Harmony, Marosi, Díaz de León, Becker, & Fernández, 1990; John et al., 1980; Matoušek & Petersén, 1973). For this reason, EEG abnormalities observed in impaired readers (especially in the case of less severe disabilities) have often been interpreted as generically due to a (more or less persistent) maturational lag in brain development. Significant progress in the field has been reached only recently by shifting the focus from testing during the resting state to recording electrophysiological parameters during the functional processes associated with specific cognitive mechanisms assumed to be impaired in people with dyslexia (i.e., linguistic, perceptual, attentional). These more recent studies have thus revealed functional differences in beta, alpha, and theta bands between people with dyslexia and controls during cognitive tasks (Galin et al., 1992; Klimesch, Doppelmayr, Wimmer, Gruber, et al., 2001; Klimesch, Doppelmayr, Wimmer, Schwaiger, et al., 2001; Milne, Hamm, Kirk, & Corballis, 2003; Spironelli, Penolazzi, & Angrilli, 2008; Spironelli, Penolazzi, Vio, & Angrilli, 2006). Results have allowed us to go beyond the generic maturational lag hypothesis of reading disabilities by precisely detecting the impaired mechanisms in specific brain regions associated with behavioral deficits in people with dyslexia. In particular, Spironelli and colleagues (2006, 2008) found important results supporting the phonological deficit hypothesis of dyslexia by using theta band as a marker of verbal working memory (see [Klimesch, 1999](#)) and beta band as a marker of high-level cognitive processing (Pantev et al., 1991; Tallon-Baudry & Bertrand, 1999). Conversely, in people with dyslexia engaged in cognitive processing, delta band—a slow EEG rhythm constituted by 0.5–4 Hz frequency and large amplitude—has not, as yet, been studied. As already mentioned, during early development, the predominant presence of delta waves can be considered a clear-cut marker of cerebral immaturity. In normal adults, very slow waves with large amplitude typical of delta band characterize the deepest stages of sleep, but whenever this rhythm occurs in the waking state, it is considered a sign of brain suffering or a pathological condition. Indeed, several studies have reported that slow waves, especially in the range of delta frequencies, often appear near structural lesions as well as in wider brain areas related to functional abnormalities of several neurological or psychiatric disorders (Babiloni et al., 2006; De Jongh et al., 2001; Wienbruch et al., 2003). Because in these clinical populations the slow wave activity has

been related to the extent of cognitive impairment (Hensel, Rockstroh, Berg, Elbert, & Schönle, 2004), abnormal delta rhythm is considered a measure of disruption of normal brain functioning and a marker of pathological significance. Therefore, data collected from healthy children compared both to adults and neurological patients provide converging evidence that delta rhythm is generally considered a clear-cut marker of cortical inhibition.

Given this solid functional significance of delta, in the present study we aimed at investigating this band in developmental dyslexia by applying our well-tested linguistic CNV paradigm (Angrilli, Dobel, Rockstroh, Stegagno, & Elbert, 2000; Penolazzi, Spironelli, Vio, & Angrilli, 2006; Spironelli & Angrilli, 2006; Spironelli et al., 2006, 2008) with a twofold purpose. First, we aimed to further clarify the neurophysiological bases of dyslexia, by localizing delta cortical sites that differentiate impaired from nonimpaired readers during the resting state. Second, by studying the linguistic functional aspects of delta band in normal and clinical populations, we sought to clarify whether and how this band can differentiate between linguistic tasks and mark the various phases of word processing. Indeed, because other EEG bands have been related to cognitive processing, whereas the delta band has been mainly used to measure immature brain functioning, the present study allowed us to use the delta band for these two distinct functional aspects within a paradigm based on active word processing. We used the same set of words in three tasks with the aim of eliciting different linguistic processes (i.e., orthographic, phonological, semantic) and hypothesized that we would find an impaired behavioral performance in people with dyslexia compared to controls, in particular during the phonological processing, because this linguistic component is the most affected in dyslexia. Similarly to previous studies, we expected to find a general increase of delta amplitude in people with dyslexia compared to controls, especially in frontal cortical sites, a result that would confirm cerebral immaturity of impaired readers. Further, in agreement with our previous findings (Spironelli et al., 2006, 2008) based on other bands (i.e., theta and beta as correlates of more specific linguistic processes), we also expected to find delta band hemispherical differences induced by experimental manipulations, thus providing evidence that also this rhythm can mark cognitive processes, although in an indirect manner (greater delta as an index of reduced cognitive processing). More specifically, during the phonological task (the most important for the phonological deficit hypothesis of developmental dyslexia) we foresaw increased left frontal activation in controls—corresponding to a reduced delta level in the same brain region. Conversely, the hypothesized deficit of people with dyslexia in the recruitment of left anterior cortical sites necessary for encoding and integrating the phonological constituents of words (Spironelli et al., 2006, 2008) was expected to be associated to an altered lateralization in the phonological task as reflected by increased delta band in this area.

Methods

Participants

EEG recordings were collected from the same sample of 42 volunteer children who participated in Spironelli et al.'s (2008) research. Participants showed an average score of 98% for right-hand dominance, according to the Edinburgh Handedness

Inventory (Oldfield, 1971) and had normal or corrected-to-normal vision. The sample of people with dyslexia consisted of 14 children (4 girls; mean age: 10.12 ± 2.23 years) selected on the basis of a documented history of dyslexia, from the Children's Neuropsychiatric Medical Facility of San Donà di Piave (Venice, Italy). Specifically, they showed impaired performance on Italian standard tests for the assessment of reading skills (mean reading speed was 1.50 ± 0.63 syllables/s, significantly less than control data: 3.93 ± 0.88 syllables/s, $t[40] = 8.90$, $p < .001$; Cornoldi & Colpo, 1998; Sartori, Job, & Tressoldi, 1995) and a normal intelligence quotient (IQ range of the participants with dyslexia was 93–112, comparable to that of controls, which ranged from 95 to 134) measured by the Wechsler Intelligence Scale for Children-Revised (Wechsler, 1986). To avoid interfering and confounding effects, children with dyslexia with associated Attention Deficit Disorder with Hyperactivity were excluded from the present research. The sample of nonimpaired readers consisted of 28 neurologically normal children, matched to the children with dyslexia on the basis of age (mean age: 10.01 ± 0.18 years, group differences for age $t[40] = 0.27$, n.s.) and gender (14 girls, group differences for gender $t[40] = 1.32$, n.s.).

Stimuli, Tasks, and Procedure

For each task, stimuli consisted of 80 pairs of bisyllabic Italian content words with average frequency in the written language (Bortolini, Tagliavini, & Zampolli, 1972). Word pairs were visually presented on a computer screen one at a time, with an intertrial interval of 3 s. The first word (W1) of each pair remained on the screen for 1.5 s, and, after an interstimulus interval of 2 s, the second word (W2) was presented and disappeared when participants responded by pressing a keyboard button with the left middle or index finger; in any case W2 was displayed for no longer than 5 s. Children were asked to compare each word pair on the basis of different linguistic criteria, corresponding to the experimental tasks: orthographic, phonological, and semantic. In the orthographic task, used to activate low-level linguistic processes (i.e., visual-perceptual), participants had to decide whether the target word W2 was written with the same case of the first word (example of matching pair: LANA-FORNO [WOOL-OVEN], mismatch pair: coda-SASSO [tail-STONE]). In the phonological task, aimed at testing the phonological deficit hypothesis of dyslexia, children were asked to perform a rhyme matching task comparing the words of each pair (example of matching pair: lana-tana [wool-den], mismatch pair: coda-latte [tail-milk]). In the semantic categorization task, used to activate lexical access and retrieval of semantic associations, participants had to judge whether the target word W2 was semantically related to the first word (example of matching pair: lana-lino [wool-linen], mismatch pair: coda-palo [tail-pole]). Each task was randomly administered in a separate block from the other tasks after a suitable resting period and preceded by a training session of 20 trials. In all tasks, 50% matches were randomly interspersed with 50% mismatch trials. In all tasks, the same set of stimuli was selected for W1 to avoid any possible effects due to differences (e.g., word length, frequency, lexical category) emerging when different sets of linguistic words are used (Penolazzi, Hauk, & Pulvermüller, 2007; Pulvermüller, 1999). This approach excludes interfering effects related to the specific type of selected stimuli; thus we can reliably argue that all statistical differences found between tasks (including the interaction of task with the other factors) are due only to the specific processes engaged by the task and not to possible confounding factors

differing between samples of stimuli (Angrilli et al., 2000; Penolazzi et al., 2006; Spironelli & Angrilli, 2006; Spironelli et al., 2006, 2008), a problem that often arises in experimental designs using different samples of stimuli for different tasks.

Data Acquisition and Analysis

Children's behavioral performance included response times (RTs) and error rates collected during the experimental session.

Cortical EEG was continuously recorded in DC mode from 38 tin electrodes, 31 placed on an elastic cap (Electrocap) according to the International 10-20 system (Oostenveld & Praamstra, 2001) and the other 7 electrodes placed below each eye (Io1, Io2), on the two external canthi (F9, F10), nasion (Nz), and mastoids (M1, M2). All cortical sites were referred to Cz and re-referenced off-line to average reference. Data were stored using SynAmps amplifiers (NeuroScan Labs, Sterling, USA). Amplitude resolution was $0.1 \mu\text{V}$; bandwidth ranged from DC to 100 Hz (6 dB/octave). Sampling rate was set at 500 Hz. Impedance was kept below $5 \text{ k}\Omega$. Because eye movement artifacts may affect delta band amplitude, especially over frontal locations, EEG data were corrected for blinks and eye movements according to Ille, Berg, and Scherg (2002) by using BESA software (Brain Electrical Source Analysis, 5.1 version).

Each EEG trial-epoch was divided into four 1024-ms time intervals (given the constraint of BESA software to use a power of 2 number of samples we needed to force the width of each interval to 512 samples corresponding to a 1024-ms interval). Thus, the fast Fourier transform (FFT) was performed using a cosine tapered window and included 512 samples/lines corresponding to 0.98 Hz resolution. Each interval represented a different processing phase required by the task: 1024 ms before Word 1 (W1) onset (baseline interval); 1024 ms after W1 onset (W1 interval); 1500 ms to 2524 ms after W1 onset (*initial* interstimulus interval, *iISI*); and 2476 ms to 3500 ms after W1 onset (*terminal* interstimulus interval, *tISI*), with *iISI* and *tISI* slightly overlapping (48 ms, $< 5\%$). These time windows were selected following other studies that investigated slow ERPs in the Stimulus 1–Stimulus 2 paradigm (Angrilli et al., 2000; Rockstroh, Elbert, Canavan, Lutzenberger, & Birbaumer, 1989; Rösler, Heil, & Röder, 1997; Ruchkin, Johnson, Maheffey, & Sutton, 1988). In line with our previous studies (Spironelli et al., 2006, 2008), the first interval of stimulus processing (W1) is clearly related to word reading, the second interval (*iISI*) refers to cognitive operations associated to the stimulus encoding in the verbal working memory (Rösler et al., 1997; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1997; Ruchkin et al., 1988), and the third interval (*tISI*) reflects the late processing of word features necessary for the comparison with the following stimulus (Rockstroh et al., 1989; Rösler et al., 1997). Artifact rejection was applied automatically to all epochs, using both an amplitude and a derivative (across time) threshold ($150 \mu\text{V}$ and $100 \mu\text{V/ms}$, respectively). Remaining epochs were then visually inspected for any residual artifacts. Overall, 14.7% of trials were rejected from controls (orthographic task: 16.1%; phonological task: 13.21%; semantic task: 14.73%) and 16.6% from dyslexic children (orthographic task: 19.31%; phonological task: 14.55%; semantic task: 15.9%). For each subject, the FFT was performed on all artifact-free epochs, which, after windowing with a cosine tapered, were averaged within each condition. The last step consisted of a normalization of delta band (nominally 0–4 Hz, effective range: 0.00–3.92 Hz) amplitude for all recorded locations by computing the percentage of delta amplitude in the

0.98–100-Hz spectral range. The normalization procedure allowed us to compare subjects with large differences in spectral energy and to measure the relative contribution of delta amplitude in comparison with the other EEG bands. Electrodes were clustered into four groups/regions of interest; thus statistical analysis included two spatial factors of two levels each: caudality and laterality (Angrilli et al., 2000). Each quadrant comprised three electrodes: anterior left (AL: Io1, Fp1, F9), anterior right (AR: Io2, Fp2, F10), posterior left (PL: P7, P3, O1), and posterior right (PR: P8, P4, O2). Although orbitofrontal electrodes (Fp1, Fp2, F9, F10, Io1, Io2) are typically used to detect and correct eye movements, after we applied the ocular artifact correction method of Ille et al. (2002), these electrodes can be considered active cortical sites, and therefore they were included in the analyses.

With regard to behavioral measures (mean error rates and RTs), analyses of variance (ANOVAs) included the between-subjects factor Group (two levels: controls vs. dyslexics) and the within-subjects factor Task (three levels: orthographic vs. phonological vs. semantic task).

On EEG data, an ANOVA was computed by including the following variables: Group (two levels: controls vs. dyslexics), Task (three levels: orthographic vs. phonological vs. semantic task), Interval (four levels: baseline vs. W1 vs. *i*ISI vs. *i*ISI), Caudality (two levels: anterior vs. posterior groups of electrodes), and Laterality (two levels: left vs. right hemisphere). The Huynh–Feldt correction was applied where sphericity assumptions were violated (Huynh & Feldt, 1970); in these cases, the uncorrected degrees of freedom, epsilon values, and the corrected probability levels are reported. Post hoc comparisons were computed using the Newman–Keuls tests, settled with $p < .05$.

Results

Behavioral Data

RTs showed a significant main effect of Group, $F(1,40) = 14.34$, $p < .001$, and Task, $F(2,80) = 63.07$, $p < .001$. More specifically, regardless of task, children with dyslexia were slower than controls (2208 ms vs. 1690 ms, respectively). In addition, for both groups, the semantic task was significantly more difficult (2343 ms) than both the orthographic (1704 ms, $p < .001$) and the phonological (1801 ms, $p < .001$) tasks. Effect sizes (Cohen's d for independent sample, Hedges correction), computed between groups for each task, showed more specific group differences. There was a “large effect” for the orthographic task (controls: 1497 ms, dyslexics: 1910 ms; $d = 0.91$, p value for differences in SD s is not significant), and “very large effects” for both the semantic (controls: 2042 ms, dyslexics: 2643 ms; $d = 1.21$, p -value for differences in SD s is not significant) and phonological tasks (controls: 1530 ms, dyslexics: 2071 ms; $d = 1.12$, p -value for differences in SD s = .06). Thus, although the effect size was similar for the latter two tasks, differences between groups tended toward significance only in the phonological task.

Error rates showed similar patterns of ANOVA results. The significant main effect of Group, $F(1,40) = 31.79$, $p < .001$, revealed that children with dyslexia made more errors than controls (14.4% vs. 6.9%, respectively). Also the factor Task showed a significant main effect, $F(2,40) = 25.08$, $p < .001$, with the semantic task characterized by greater error rates (14.2%) than both the phonological (7.9%, $p < .001$) and the orthographic tasks (9.9%, $p < .001$). Differently from the RTs, effect sizes

computed on error rates showed a significant difference between groups. Namely, there were “very large effects” in both the orthographic (controls: 6.74%, dyslexics: 13.03%; $d = 1.11$, p -value for differences in SD s is not significant) and semantic tasks (controls: 10.89%, dyslexics: 17.5%; $d = 1.29$, p -value for differences in SD s is not significant) and a “huge effect” in the phonological task (controls: 3.12%, dyslexics: 12.68%; $d = 1.9$, p -value for differences in SD s $< .001$). Therefore, only in the phonological task did the effect size between groups reach significance.

EEG Data

Figure 1 shows a panoramic view of all normalized (0–100 Hz) EEG bands in the two groups of subjects. It is evident that the delta band has a very strong impact on the whole spectrum, especially in patients, its percentage being more than half of the

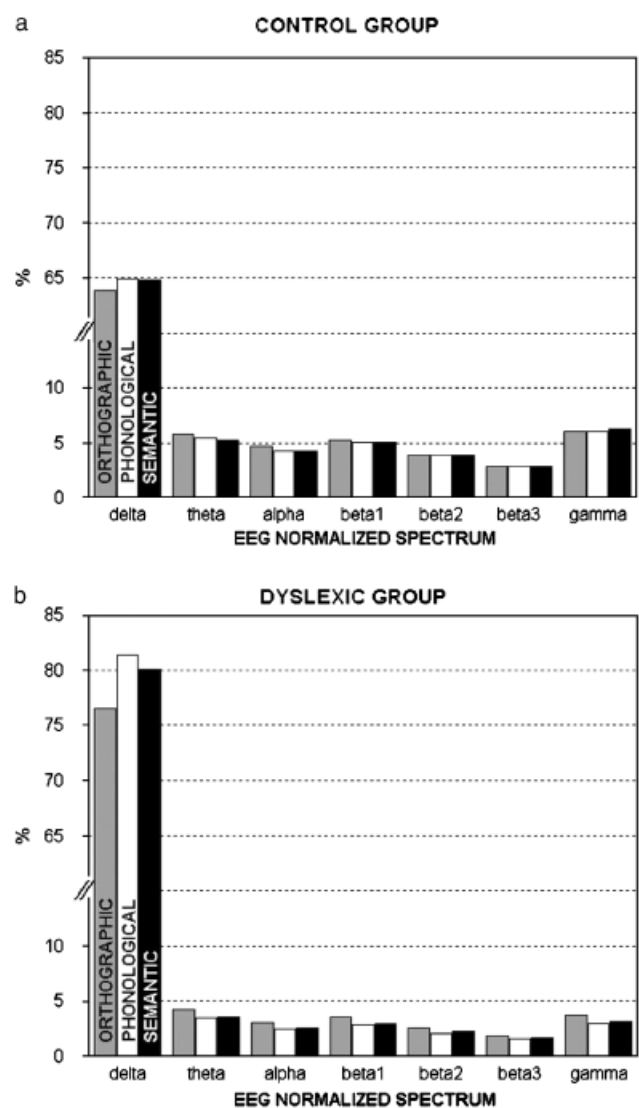


Figure 1. Grand mean percentages of normalized (0–100 Hz) EEG bands across tasks in (a) controls and (b) children with dyslexia (delta band: 0–4 Hz, theta band: 4–8 Hz, alpha band: 8–12 Hz, beta1 band: 12–20 Hz, beta2 band: 20–28 Hz, beta3 band: 28–35 Hz, gamma band: 35–50 Hz; gray columns: orthographic task, white columns: phonological task, black columns: semantic task).

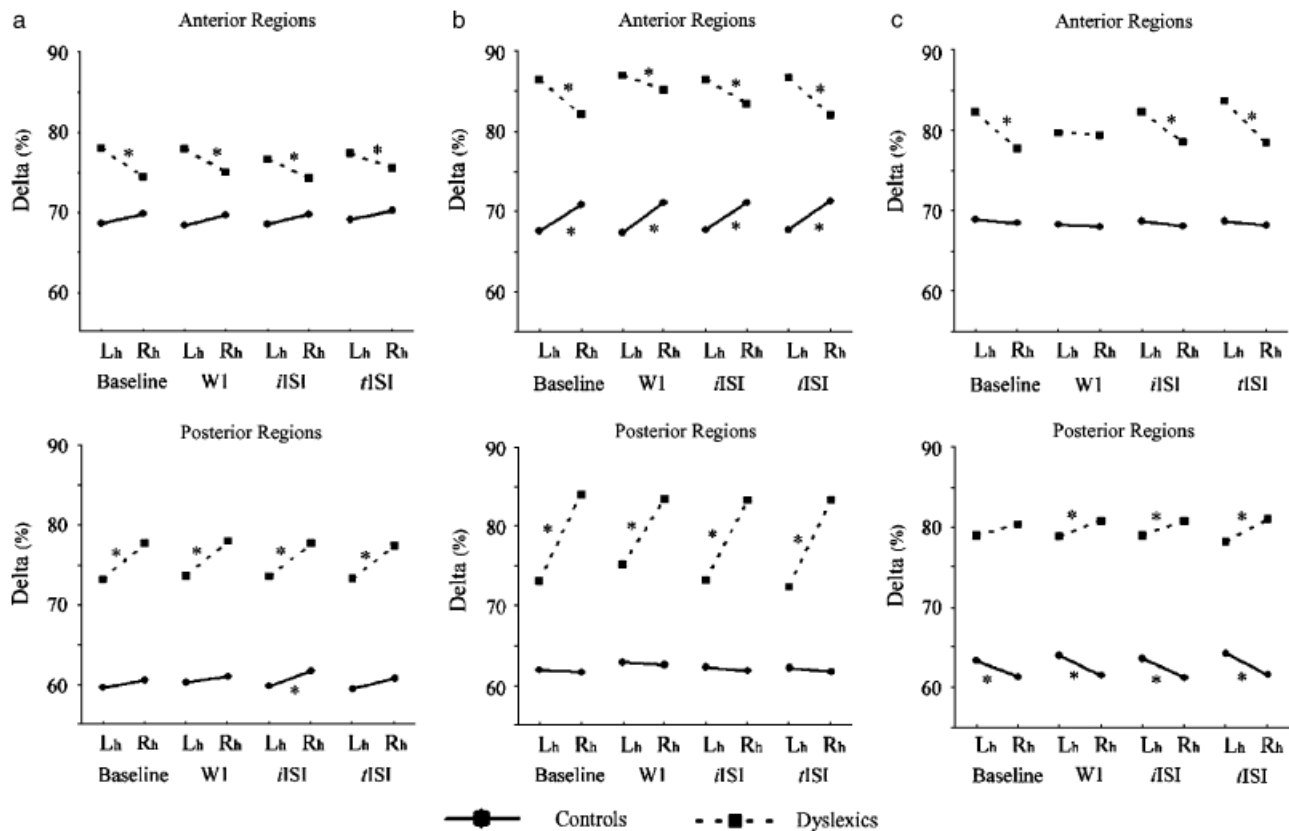


Figure 2. Percentages of normalized delta band (0.00–3.92 Hz) in the five-way Group $\times$ Task $\times$ Interval $\times$ Caudality $\times$ Laterality interaction. Comparison between cortical activity of controls (full line) and children with dyslexia (dashed line) during the four different phases of word processing in anterior (upper panel) and posterior (lower panel) regions for (a) orthographic, (b) phonological, and (c) semantic tasks. Significant post hoc test results ($p < .05$) are marked by asterisks for within group differences only.

entire spectrum in controls (about 65%, Figure 1a) and reaching nearly 80% in children with dyslexia (Figure 1b).

Another salient point emerging from the figure is the inverted pattern between delta and all remaining EEG bands when considering one group compared to the other. Indeed, children with dyslexia had greater delta percentages and lower levels in all the remaining EEG bands, whereas controls had smaller delta percentages and higher levels in all the remaining EEG bands. Considering the delta rhythm, which is the main issue of the present study, dyslexic children showed a clear-cut task modulation, which was larger when compared both to their own other bands (Figure 1b) and to the same band of controls (Figure 1a). Interestingly, the highest level of the delta band was reached by children with dyslexia during the phonological task.

ANOVA revealed a significant main effect of Group, $F(1,40) = 68.19$, $p < .001$, with children with dyslexia showing a higher delta percentage than controls (79.15% vs. 65.34%, respectively). Statistics showed also a significant main effect of Task, $F(1,40) = 3.70$, $\epsilon = 1.00$, $p < .05$, although post hoc tests failed to reveal significant amplitude differences between tasks. The main effect of Caudality was also significant, $F(1,40) = 15.44$, $p < .001$: anterior areas exhibited greater delta percentages compared to posterior locations (74.70% and 69.79%, respectively). Focusing on the most interesting significant interactions, that is, those that included the Group factor, the ANOVA revealed both a significant Group $\times$ Caudality $\times$

Laterality three-way interaction, $F(1,40) = 10.00$, $\epsilon = 1.00$, $p < .01$, and a significant Group $\times$ Interval $\times$ Caudality $\times$ Laterality four-way interaction, $F(1,40) = 6.04$, $\epsilon = .80$, $p < .01$. The pattern of cortical activity of these interactions can be better interpreted by considering the significant five-way Group $\times$ Task $\times$ Interval $\times$ Caudality $\times$ Laterality interaction, $F(1,40) = 2.62$, $\epsilon = .65$, $p < .05$, which included the effects observed in the former two interactions (Figure 2).

Looking at the post hoc effects, orthographic, phonological and semantic tasks elicited a different delta activity distribution in normal and impaired readers. During the phonological task (Figure 2b) controls showed, in all experimental conditions, greater delta activity over right versus left anterior regions ($p < .001$) and bilateral activity over posterior areas, whereas children with dyslexia exhibited a reversed lateralization pattern over anterior locations, with greater delta activity in left versus right anterior quadrants ($p < .01$) and in right versus left posterior locations ($p < .001$). In participants with dyslexia, the semantic task elicited a pattern of delta lateralization similar to that found during the phonological task (Figure 2c): higher delta percentages at anterior left versus right quadrants ($p < .001$, except for W1 phase, marked by bilateral delta activity) and at right versus left posterior areas ($p < .05$, except for the baseline interval, in which activity was bilateral). Instead, in all intervals of the semantic task, controls exhibited bilateral delta distribution over anterior areas and greater delta activity over left versus right

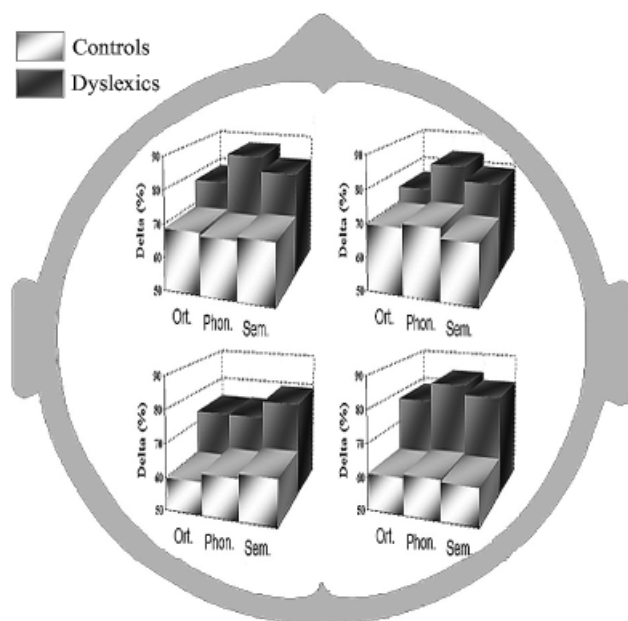


Figure 3. Delta band activity of children with dyslexia and controls (dark and light bars, respectively) throughout the tasks in the four cerebral quadrants (factor “Interval” collapsed).

posterior locations ($p < .05$). In the orthographic control task (Figure 2a), normal readers showed a bilateral hemispherical distribution of delta band in most conditions ($p < .05$) with the exception of the *i*ISI, which was characterized by a higher delta level in right posterior sites. Instead, similar to their response to other tasks, children with dyslexia showed greater delta activity over left versus right anterior brain regions ($p < .01$) and over right versus left posterior locations ($p < .001$). Although the pattern exhibited by children with dyslexia (i.e., higher delta levels over anterior left and posterior right locations) was in general undifferentiated across tasks, in this group the phonological task elicited an overall greater delta amplitude with respect to semantic and orthographic ones ($p < .01$; see Figures 2 and 3, the last showing the effects with the factor Interval collapsed). Indeed, in children with dyslexia, phonological processing produced the highest values of delta levels ($p < .001$), which reached the maximum amplitude on anterior left regions. Furthermore, during the phonological task, children with dyslexia showed the widest interhemispheric differences, delta values being higher on right posterior regions ($p < .01$; Figure 3).

Discussion

The present research aimed at investigating the modulation of the delta band across different linguistic processes in developmental dyslexia, using a well-validated linguistic paradigm (Angrilli et al., 2000; Spironelli & Angrilli, 2006). The main purpose was to better clarify the neurophysiological correlates of this developmental disorder by testing the phonological deficit hypothesis and the maturational lag hypothesis and, at the same time, to enlarge the functional meaning of the delta band.

The linguistic impairment of children with dyslexia—originally assessed by neuropsychological tests used for group selection—was confirmed by behavioral results, as children with

dyslexia performed all tasks worse than controls. In particular, regardless of task and in line with their reduced reading speed, RTs revealed an overall delay (of about 500 ms) in children with dyslexia compared to controls. It is plausible to attribute this effect to their impaired mechanism of grapheme–phoneme conversion, which affects, from the first stages, all the linguistic processes. Also their error rates were significantly higher compared to controls, although in general the percentages were relatively good and widely below chance level. Interestingly, more sensitive analyses showed that, compared to controls, children with dyslexia made more errors specifically during the phonological task (i.e., nearly a third more errors carried out in the phonological compared to both the semantic and orthographic tasks). The severe failure of children with dyslexia in this task, which specifically required phonological processing, underlines their reduced meta-phonological skills and supports the phonological deficit hypothesis of developmental dyslexia.

As regards the electrophysiological measures, a first result was the higher levels of relative delta percentage in dyslexic children compared with controls, independent of experimental variables. In line with most previous studies, which investigated this developmental disorder in resting conditions (Ahn et al., 1980; Fonseca et al., 2006; González-Garrido et al., 1993; Harmony, Hinojosa, et al., 1990; John et al., 1983), this result suggests a delayed maturation of brain structures in disabled readers. Thus, it is possible to state that our data, on first appearance, confirm the maturational lag hypothesis of dyslexia. We also found the significant main effect of Caudality, proving that groups were marked by overall higher delta percentages over the anterior compared to the posterior locations, in agreement with developmental studies describing frontal lobes as the last cerebral structures that complete maturation (Benninger, Matthis, & Scheffner, 1984; Gasser, Jennen-Steinmetz, Sroka, Verleger, & Mocks, 1988). The three-way Group $\times$ Laterality $\times$ Caudality interaction showed differences along the antero-posterior axis mostly in controls, as children with dyslexia exhibited higher levels of delta percentages in both anterior and posterior sites. Therefore, this result confirms that our dyslexic sample was marked by a general cortical immaturity, because also their posterior sites were relatively inhibited (greater delta amplitudes) compared to controls.

The most interesting finding of the present study is represented by delta band changes associated with the experimental manipulations. Although each task revealed quite consistent results across different time intervals, we found several task-dependent delta modulations: thus it is possible to state that the specific process required by each task, rather than by each interval, induced differentiated patterns of activity (see Figures 2 and 3). An important result is the greater delta amplitude found over dyslexic children's anterior locations during the phonological compared to both the semantic and orthographic tasks. This pattern of relative inhibition of phonological processes was not found in controls, thus it suggests a functional phonological impairment in the frontal cortex that is highly consistent with the phonological deficit hypothesis of dyslexia.

Further relevant results were provided by analysis of hemispheric lateralization. Controls showed task-dependent patterns of delta activity: during the orthographic task (Figure 2a), they had a bilateral distribution of this rhythm at both anterior and posterior locations, a pattern expected to be related more to a

visuo-perceptual analysis than to effective linguistic processing. Instead, during the phonological task (Figure 2b), normal readers exhibited bilateral delta distribution over posterior clusters and right delta lateralization over anterior ones. Most of the literature provides converging evidence of the functional interpretation of the delta band as an index of cortical inhibition (Babiloni et al., 2006; De Jongh et al., 2001; Wienbruch et al., 2003). Therefore controls' reduced delta activity over left versus right anterior sites specifically during the phonological task suggests a relative activation of left frontal sites. This result was expected as a consequence of task manipulation and from the consistent literature that, using fMRI, PET, and ERP methods, shows converging evidence of the main involvement of the left frontal cortex, especially Broca's area, in phonological processing (Angrilli et al., 2000; Burton, 2001; Burton, Small, & Blumstein, 2000; Price, 1998; Spironelli & Angrilli, 2006). A quite different pattern was found during the semantic task in normal readers (Figure 2c), as we found a bilateral delta distribution over frontal quadrants and greater left compared to right delta amplitudes at posterior sites, indicating a relative right posterior activation. This observation is in line with many studies, especially those employing EEG methods, that have suggested the critical involvement of categorization networks and lexical-semantic storages in posterior areas of both hemispheres (Abdullaev & Posner, 1997; Angrilli et al., 2000; Poldrack et al., 1999; Seghier et al., 2004; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). EEG activity measured in our control group provides the first evidence that the delta band is capable of distinguishing between different linguistic processes, with activity localization in line with the literature. That such results emerged notwithstanding the use of the same stimuli, aimed at controlling potentially confounding variables, plays against the possibility of detecting significant task differences in both the spatial and temporal dimensions. Given this discriminative power of the delta band in normal readers even during different linguistic processes, the use of this band to measure only basic level differences between groups appears, at the very least, restrictive. Unlike the controls' ability to differentiate tasks and linguistic processes, children with dyslexia showed essentially the same pattern of delta activity, that is, greater delta percentages on anterior left sites and on right posterior locations—thus suggesting a relative activation of right frontal and left posterior cortical regions. Therefore, at frontal sites, hemispheric asymmetry of the dyslexic childrens' activity was reversed compared to that of controls; furthermore, this asymmetry was not modulated by the task, thus suggesting a functional inability of impaired readers to recruit left frontal linguistic networks necessary for reading.

During the phonological task, the dyslexic childrens' inverted lateralization over anterior clusters (Figure 2b, upper row) suggests a specific impairment in those brain regions of the left hemisphere involved in the segmentation and assembling of phonological information (Burton, 2001; Burton et al., 2000), a result that supports the phonological deficit hypothesis of developmental dyslexia (Ramus, 2003, 2004; Ramus et al., 2003; Shaywitz, 1998; Shaywitz & Shaywitz, 2005; Shaywitz et al., 2002; Temple et al., 2001). In addition, in impaired readers the phonological processing induced the highest levels of delta amplitude over left anterior sites when compared to the other two tasks (Figure 3), further confirming that the specificity of their disorder is phonological in nature.

As regards the posterior locations, the dyslexic childrens' higher delta levels on the right side corresponding to greater relative activation of the left hemisphere (Figure 2, lower row) are in agreement with Rumsey et al. (1999), who found a significant activation of left angular gyrus in dyslexic adults with the worse reading performance. By way of contrast, several studies have found reduced activation of the same cortical regions during word processing, suggesting a disruption of the left posterior areas involved in reading (Brunswick et al., 1999; Démonet et al., 2004; Paulesu et al., 2001; Shaywitz et al., 1998, 2002; Temple et al., 2001). The increased left posterior activation observed in our children with dyslexia seems to contradict past fMRI results. However, this inconsistency may be due to instrumentation and methodological differences: metabolic measures might be more sensitive to group differences in activation, whereas EEG methods might be more sensitive to relative differences within groups, both for task and for topographical distribution (e.g., left-right/antero-posterior asymmetries). Our results may provide support to this interpretation, because in the left posterior quadrants controls exhibited lower delta percentages than children with dyslexia (on average about 12–14% less), an effect which is relatively larger than left–right delta significant differences found within both groups. Thus, in agreement with fMRI findings, our data suggest large group differences in delta activity in the left posterior sites, with children with dyslexia showing overall less activation (i.e., more delta) than controls, but delta EEG measures appearing more sensitive to small differences within groups (i.e., to factors such as Task, Lateralization, and Caudality) than fMRI methods. Concerning the functional meaning of this increased left posterior activation in children with dyslexia, which marked phonological and orthographic tasks only, we assume it represents the dyslexic childrens' failure in shifting from the visual analysis to the subsequent phases of word processing. Therefore, this finding suggests that impaired readers are blocked in the grapheme visual processing of words (typical of the orthographic task) also during the phonological task.

In conclusion, using delta EEG band analysis in a validated linguistic paradigm, we found clear-cut evidence of greater brain electrical immaturity in our sample of impaired readers when compared to controls, as they showed a delayed maturation not only in anterior but also in posterior locations. In addition, controls exhibited task-dependent patterns of delta activity whereas dyslexic children showed the reversed hemispheric activity—that is, greater delta percentages on both anterior left and posterior right locations—without specific task modulations. Because cortical inhibition was also detected in both anterior and posterior clusters of the left hemisphere, reaching the highest values during phonological processing, the present data support the phonological deficit hypothesis as a more comprehensive explanation of developmental dyslexia. From a methodological point of view, the delta band, which traditionally has been found to signal only coarse activation differences between groups in a resting condition, turned out to be sensitive to the linguistic task manipulations of our paradigm. Therefore, the task-dependent delta modulation found in this study highlights the potential utility of this band as a new tool to specifically investigate cognitive functioning in normal and clinical populations and represents a complementary method that can be added to more popular and traditional EEG bands sensitive to cognitive processing.

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