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Behavioural and event-related potentials evidence for pitch discrimination deficits in dyslexic children: Improvement after intensive phonic intervention

Andreia Santos [a,*], Barbara Joly-Pottuz [a,b], Sylvain Moreno [a],
Michel Habib [a,b], Mireille Besson [a]

[a] *Institut de Neurosciences Cognitives de la Méditerranée, Marseille, France*
[b] *Department of Pediatric Neurology, CHU Timone, Marseille, France*

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Abstract

Although it is commonly accepted that dyslexic children have auditory phonological deficits, the precise nature of these deficits remains unclear. This study examines potential pitch processing deficit in dyslexic children, and recovery after specific training, by measuring event-related brain potentials (ERPs) and behavioural responses to pitch manipulations within natural speech. In two experimental sessions, separated by 6 weeks of training, 10 dyslexic children, aged 9–12, were compared to reading age-matched controls, using sentences from children's books. The pitch of the sentence's final words was parametrically manipulated (either congruous, weakly or strongly incongruous). While dyslexics followed a training focused on phonological awareness and grapheme-to-phoneme conversion, controls followed a non-auditory training. Before training, controls outperformed dyslexic children in the detection of the strong pitch incongruity. Moreover, while strong pitch incongruities were associated with increased late positivity (P300 component) in controls, no such pattern was found in dyslexics. Most importantly, pitch discrimination performance was significantly improved, and the amplitude of the late positivity to the strong pitch incongruity enhanced, for dyslexics after a relatively brief period of training, so that their pattern of response more closely resemble those of controls.

Keywords: Dyslexia; Pitch discrimination; ERPs; Remediation

1. Introduction

Developmental dyslexia is defined as an unexpected, specific, and persistent failure to acquire efficient reading skills despite conventional instruction, adequate intelligence, and sociocultural opportunity (Démonet, Taylor, & Chaix, 2004). At the brain level, the origin of dyslexia may result from an atypical early development, due to genetic or epigenetic factors (Grigorenko, 2001) of the left hemisphere's cortical architectonic organization (Galaburda & Kemper, 1979; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985), and/or subcortical (Livingstone, Rosen, Drislane, & Galaburda, 1991) and cortico–cortical connectivity (Klingberg et al., 2000; Pugh et al., 2000; Silani et al., 2005).

Functionally, there is strong evidence that reading abilities have a foundation in early speech perception abilities (Molfese et al., 2002; Molfese & Molfese, 2002). Current theories of dyslexia emphasize difficulties in auditory phonological processing (for a review see Habib, 2000). The hypothesis that dyslexic children come to the task of learning to read with poorly specified phonological representations (Snowling, 2001; Swan & Goswami, 1997), resulting in grapheme-to-phoneme decoding deficits, has been proposed to explain their reading disabilities. However, the precise mechanisms underlying the proficient use of these skills in reading remain unclear. As a possible cause of impaired phonological representations, Tallal (1980) proposed an influential – albeit controversial – theory, following which impaired temporal acoustic processing constrains proper speech perception and, as a result, compromises the development of strong and stable

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* Corresponding author at: CNRS, INCM, LM2, 31, Chemin Joseph Aiguier, 13402 Marseille Cedex 20, France. Tel.: +33 491 16 45 19; fax: +33 491 77 49 69.
E-mail address: a.santos@incm.cnrs-mrs.fr (A. Santos).

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phoneme representations, and reading acquisition (Tallal, 2004).

Interestingly, Merzenich et al. (1996) and Tallal et al. (1996) were able to demonstrate significant improvement in temporal processing, speech discrimination and listening comprehension, by manipulating temporo-spectral characteristics of human speech in intensive daily auditory exercises in language impaired children. Such improvements were subsequently related to specific functional reorganization of language areas (Aylward et al., 2003; Shaywitz et al., 2004; Temple et al., 2001, 2003).

Several studies, based on temporal processing tasks, have attempted to specify the perceptual auditory deficits in dyslexia. Deficits in timing skills (Overy, 2003), amplitude modulation detection (McAnally & Stein, 1996; Menell, McAnally, & Stein, 1999), amplitude envelop onsets (Goswami et al., 2002), stream segregation (Helenius, Uutela, & Hari, 1999), and discrimination of temporal information (Kujala et al., 2000) have been found in dyslexics.

One of the most relevant methods to examine the time course of language processing is the event-related potentials (ERPs) method, which has been widely used with dyslexics during these last years (for reviews see Connolly, D'Arcy, Newman, & Kemps, 2000; Lachmann, Berti, Kujala, & Schröger, 2005; Lyytinen et al., 2005; Robichon, Besson, & Habib, 2002). Overall, these studies provided evidence for impaired cortical sound perception and discrimination in dyslexic children. Recently, benefiting from the excellent temporal resolution of the ERP method, Giraud et al. (2005) have shown that auditory discrimination deficits of voiced–unvoiced contrasts in adult dyslexics with persistent reading difficulties are associated with a specific time-coding impairment of the successive components of the acoustic signal.

There is nevertheless evidence, from studies using large and diverse batteries of psychoacoustic tasks, that dyslexic's auditory deficits may not be limited to the temporal aspects of auditory processing (Ahissar, Protopapas, Reid, & Merzenich, 2000; Amytay, Ahissar, & Nelken, 2002). For instance, Moisescu-Yiflach and Pratt (2005), have demonstrated, using both ERP waveform analysis and current density source estimation, that auditory discrimination in dyslexics was impaired not only for temporal but also for frequency cues. These results are in line with the hypothesis that pitch discrimination is also impaired in dyslexia (Ahissar et al., 2000; Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Cacace, McFarland, Ouimet, Schrieber, & Marro, 2000; Hari, Stääkilahti, Helenius, & Uutela, 1999; McAnally & Stein, 1996; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999). Baldeweg et al. (1999) have, for instance, shown that the ERP to pitch changes differed between young dyslexic adults and controls, whereas no differences were found for duration changes. The authors suggested that this deficit in pitch discrimination was possibly linked to "a persistent sensory deficit in monitoring the frequency of incoming sound" (Baldeweg et al., 1999, p. 495). Likewise, children at familial risk for dyslexia have more difficulties than controls to detect frequency deviants (Maurer, Bucher, Brem, & Brandeis, 2003). While it is not yet clear how pitch discrimination relates to the phonological impairment leading to dyslexia, the ability to discriminate global pitch contour of sound sequences seems to covary with the development of phonological representations and reading skills (Foxton et al., 2003).

Finally, complexity and processing demands also yield ERP differences between dyslexics and normal readers (Lyytinen et al., 2005). Kujala et al. (2000) reported that adults with dyslexia failed to detect temporal changes occurring in the middle of a complex stimulus pattern, yet easily detected by the control group. However, no differences between groups were found with a simpler two-tone pattern (see also Kujala, Belitz, Tervanieni, & Näätänen, 2003).

Based on the findings that dyslexics may have deficits in pitch processing (Baldeweg et al., 1999) and may also be impaired, compared to controls, when stimuli are part of a complex stimulus pattern (Kujala et al., 2000), the first aim of the present experiment was to test the hypothesis that dyslexic children may have increased difficulties discriminating pitch deviants when they are embedded in a complex and rapid presentation of auditory stimulus. To this end, we examined the processing of pitch changes included in natural speech. In order to use a material as ecological and interesting as possible for children, we used sentences from children's books. The final word of the sentences was either spoken at a natural pitch level, or was parametrically manipulated to create weak (35% increase in pitch) or strong (120% increase in pitch) incongruities (see Section 2). Results of previous ERPs studies, using the same materials (Magne, Schön, & Besson, 2006; Moreno & Besson, 2006), have shown that for children with no reading disabilities, the strong incongruity was the easiest to detect. Moreover, at the ERP level, the strong incongruity elicited a large positive component peaking around 300 ms post-stimulus onset and probably belonging to the P300 family of components. P300-like components have been reported in a large number of experiments and are generally interpreted as reflecting the processing of deviant and task relevant stimuli (Donchin & Coles, 1988; Lyytinen et al., 2005). If dyslexic children encounter difficulties in processing frequency deviants, specifically when frequency changes are embedded within complex stimulus patterns (Kujala et al., 2000), the amplitude of the P300 to pitch changes in sentence contexts should be smaller and the percentage of correct detection lower than for children with no reading disabilities. In order to test these specific hypotheses, a group of normal reading children, matched for reading age, was also included in this study.

The second aim of the present study was to uncover neurophysiological changes following remedial training in dyslexic children. To this aim, we used a Test 1 – Training – Test 2 procedure and we recorded ERPs before and after training. Previous studies have indeed highlighted the sensitivity of different ERP components, and, in particular the late positivity, to learning and memory processes (Johnson, Pfefferbaum, & Koppel, 1985; Molfese & Molfese, 1997; Paller, Kutas, & Mayes, 1987). Dyslexic children were first tested in the pitch discrimination task, using both ERPs and behavioural measures. Then, they followed a 6-weeks session of intensive phonological training inspired by two remediation techniques previously validated in French (Habib et al., 1999, 2002; Magnan, Ecalle, Veuillet,

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& Collet, 2004). Finally, they were again tested in the same pitch discrimination task, using the same measures. We hypothesized that if remediation in children with dyslexia is efficient in improving pitch processing in complex auditory sequences such as natural speech, the level of performance (measured by error rates and reaction times (RTs)) should increase after training. Concomitantly, at the electrophysiological level, the ERP pattern of dyslexic children should be more similar to controls after than before training. While training may influence different stages of information processing, and consequently different ERP components, the late positivity (P300) has recently been shown to be particularly sensitive to learning effects (Key, Molfese, & Ratajczak, 2006; Rose, Verleger, & Wascher, 2001). Thus, the amplitude of the P300 component to strong incongruities should be larger after than before training, that is, when the correct detection of pitch changes increases. To directly test the influence of remedial training, and to examine its neurophysiological basis, we compared behavioural and electrophysiological data in Tests 1 and 2, not only in our dyslexic population, but also in a reading-age matched non-dyslexic population that followed a non-auditory training (see below).

Table 1
Summary of mean results on the neuropsychological tests for dyslexic children before training

Task	Performance (S.D.)
WISC-III verbal subtests	
Similarities (/19)	11.1 (3.28)
Arithmetic (/19)	8.3 (3.74)
Vocabulary (/19)	10 (3.27)
Digit span (/19)	6.3 (2.58)
WISC-III performance subtests	
Picture completion (/19)	12.2 (2.62)
Block design (/19)	9.8 (4.16)
NEPSY visuo-spatial	
Design copying (/19)	9.2 (3.71)
Arrows (/19)	12.8 (3.49)
NEPSY attention and executive function	
Tower (/19)	10.5 (3.21)
Auditory attention and response set (/19)	11 (1.25)
Visual attention (/19)	9.8 (2.20)
Design fluency (/19)	9.4 (2.56)
Memory assessment	
BEM 84 Signoret (/84)	56.2 (8.50)
Visual memory	
Visual span (/12)	4.9 (.99)
Rhythmic structure	
Stamback (/21)	12 (3.8)
Analogical reasoning	
Raven PM 47	60th percentile (26.46)

2. Methods

2.1. Subjects

Ten dyslexic boys (mean age: 9.8 years; S.D. = 1.2 years) were recruited from a special class for dyslexics within an elementary school in Marseille, France. All children were right-handed. They were selected on the basis of their reading level (i.e. more than 18 months below chronological age), assessed with the Alouette's standardized reading test (Lefavrais, 1965). Non-verbal intelligence was assessed by the Raven's Progressive Matrices (1981), which located the group in the 60th percentile. Moreover, before the experiment, each participant received a large battery of neuropsychological tests. It is important to note that this evaluation aimed exclusively at diagnosis confirmation and dyslexia subtyping (see Table 1). It allowed us to exclude dyslexia possible comorbidities such as attention, mathematics, oral language, memory and visuo-spatial disorders.

Further assessment of reading strategies included pseudowords, regular and irregular words reading, as well as several phonological awareness and spelling tasks (see Table 2). This battery served as a baseline for assessing the impact of

Table 2
Summary of results of Student *t*-test on the reading skills measures for dyslexic children before (S_1) and after training (S_2)

Task	Performance			
	S_1	S_2	*t*	*p* (dl = 9)
Allouette	33.89 (13.51)	30.63 (13.58)	1.70	.12
Spelling pseudowords (/23)	8.22 (5.59)	10.5 (4.63)	−1.99	.08
Phonemic fluency	14.22 (3.07)	15.75 (2.55)	−1.94	.08
Semantic fluency	24.22 (6.92)	27.13 (7.86)	−1.70	.12
Phonological awareness				
1st syllable deletion (/16)	15.44 (1.01)	15.63 (.74)	−.50	.63
1st consonant deletion CVC (/16)	11.22 (4.99)	14.88 (1.36)	−2.30	**.05**
1st consonant deletion CCV (/10)	6.78 (2.73)	9.13 (1.13)	−2.53	**.03**
Auditory acronyms (/10)	10.78 (4.09)	14.5 (1.85)	−3.04	**.01**
Rhymes judgement (/10)	6.67 (2.83)	8 (2)	−6.21	**.001**
Reading strategy				
Pseudowords (/20)	12.44 (4.50)	13.5 (4.84)	−1.96	.08
Regular words (/10)	9 (1.41)	9.38 (1.41)	−1.57	.15
Irregular words (/10)	4.33 (3.32)	5.88 (2.80)	−2.29	**.05**
Spelling				
Phonological errors	26.44 (14.74)	21.25 (15.51)	3.05	**.01**
Grammatical errors	21.22 (12.74)	14.5 (8.47)	1.99	.08
Usual rules errors	18.44 (7.40)	10.88 (4.58)	4.61	**.001**

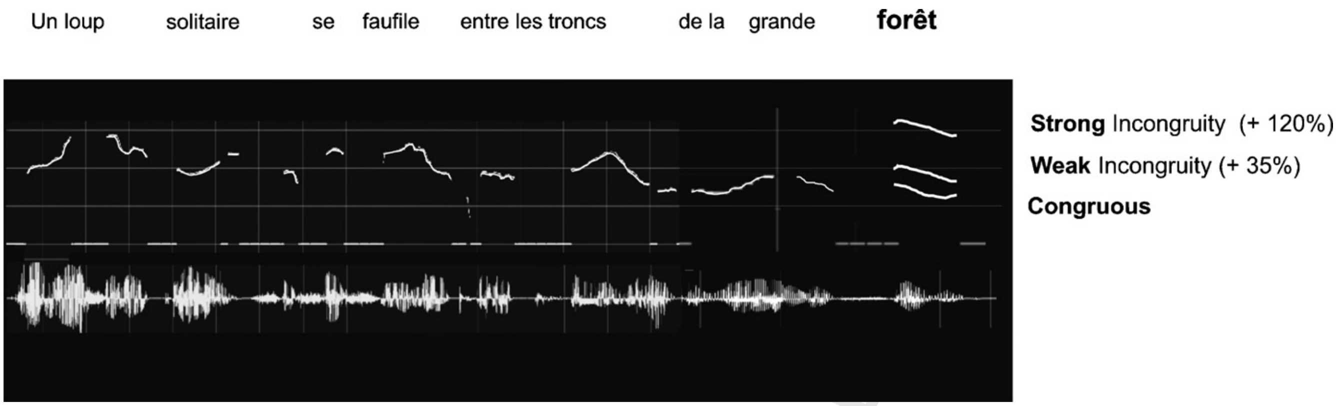

Fig. 1. Spectrogram of a sentence presented in the experiment. The speech signal is illustrated for the sentence "Un loup solitaire se faufile entre les troncs de la grande forêt" (Literal translation: "A lonely wolf worked is way through the trees of the big forest"). The final word is prosodically congruous or incongruous with strong or weak pitch manipulations.

the remediation program in the dyslexic group and was repeated after training along with a specific ERP protocol (see below).

In addition, a control group of 10 normal-reading children (six boys and four girls, eight right-handers and two left-handers,[1] mean age: 8.8 years; S.D. = .29 years) matched for reading level did also participate to the behavioural and ERP experiments. In French public schools, all third grade children are systematically tested on their reading, writing and spelling skills. According to this National Program of Education Assessment (2004), all children in the control group were classified as normal readers. Consequently, they did not receive further reading and neuropsychological evaluation.

Children in both groups followed a Test 1 – Training – Test 2 procedure. While the training phase was different for the dyslexic and control groups (see below), Tests 1 and 2 were identical. This allowed to control for test–retest procedures, for the effects of general development and maturation (children were about 3 months older in Test 2 than in Test 1), as well as for cognitive stimulation (the same stimuli as in Test 1 were repeated in Test 2).

All, dyslexic and control, children were native speakers of French and had normal or corrected-to-normal vision, normal audition and no known neurological deficits or overt physical handicap. Parental consent to be involved in the study was obtained for all children and the study was approved by the local ethics committee.

2.2. *Stimuli*

Stimuli comprised 72 French spoken declarative sentences that were issued from children's books (e.g. "Dans la barque se tient l'ennemi de Peter Pan, le terrible pirate"/"In the boat is the enemy of Peter Pan, the terrible pirate"). Sentences always ended with bi-syllabic words (e.g. "pirate") and their meaning was always easy to understand. An equal number of sentences (24) were presented in each of three experimental conditions: the final word was prosodically congruous, weakly incongruous or strongly incongruous (see Fig. 1). Consequently, each child listened to a total of 72 sentences. Moreover, three lists of stimuli were built so that each sentence was presented in each condition across children. The pitch of the last word was increased using the software WinPitch (Martin, 1996) by 35% for the weak incongruity, and by 120% for the strong incongruity. The mean duration of the sentences was 3.95 s (S.D. = .65). This material has been used in previous experiments with adults (Schön, Magne, & Besson, 2004) and children (Magne et al., 2006; Moreno & Besson, 2006). Sentences were recorded in a soundproof room using a digital audiotape and a sampling rate of 44.1 kHz.

2.3. *Procedure*

The experiment was conducted over a 12-weeks period and comprised three phases (two testing sessions separated by 6 weeks of training). In the first phase, which lasted for about 2 weeks, all children, controls and dyslexics, were tested individually, in a session that lasted for approximately 2 h, using both behavioural and ERP measures. Children were seated in an electrically shielded room. The experiment comprised 3 blocks of 24 trials each, and began with a practice block (comprising 6 sentences that were not repeated in the experimental blocks) to familiarize the child with the task. Children were required to listen attentively, through headphones, to the sentences that were presented in a pseudo-random order (no more than three successive sentences belonging to the same experimental conditions) within each block. They were asked to decide, as quickly and accurately as possible, by pressing one of two response keys, whether the pronunciation of the sentence final word was normal or strange (i.e., something was wrong). The hand of response was counter-balanced across children. In the second phase, the 6-weeks training period, dyslexic children followed daily phonological exercises (rhyme judgement, counting the syllables of words, word repetition and first syllable detection) without verbal feedback (Habib et al., 1999, 2002). They also received audio-visual training (*Play-On*®) twice a week in sessions of 20 min. This training, developed by Danon-Boileau and Barbier (2000), focuses on voicing opposition between pairs of phonemes (for further details, see Magnan et al., 2004).

Insofar as children in the control group were all normal readers, it was neither relevant nor ethical to use the same training as with dyslexic children. Rather, they followed a painting training, twice a week for 40 min in their school, for a period of 8 weeks. The training was based upon abstract painting exercises, implemented through art games. The objectives were to learn how to mix pigments to make colours and to create works of art based on movement. This group also served as a control group for another experiment (Moreno & Besson, 2006).

All subjects completed their respective programs and had on average the same number of hours of training (dyslexics: 11 h; controls: 10.6 h).

In the third phase, at the end of the training program, both groups were tested again on the pitch discrimination task, in similar experimental conditions as described for phase 1. Thus, the 20 children were again tested individually in a session that lasted for approximately 2 h. Dyslexic children were also reassessed on their reading skills, using the same measures as described above (see Table 2).

2.4. *ERP recordings*

EEG was recorded for 2200 ms starting 150 ms before the onset of the stimulus, from 28 scalp electrodes mounted on an elastic cap. Standard left and right hemisphere positions were recorded over frontal, central, parietal, occipital, and temporal areas (International 10/20 system sites: Fz, Cz, Pz,

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[1] While it was impossible, for practical reasons, to exactly match children in the dyslexic and control groups on sex and handedness, complementary analysis on error rates, reaction times and electrophysiological data revealed that these factors did not exert a significant influence on these results. Thus, for instance, results remain unchanged when excluding the two left-handed children.

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Table 3
Summary of results on the modified error rates and RTs

Effect	ANOVAs					
	Modified error rates			RTs		
	dl	*F*-value	*p*-Value	dl	*F*-value	*p*-Value
Between subjects analysis						
Group	(1, 18)	26.62	**.001**	(1, 18)	11.57	**.003**
Session	(1, 18)	39.13	**.001**	(1, 18)	8.36	**.01**
Congruity	(2, 36)	62.67	**.001**	(2, 36)	35.06	**.001**
Group × session	(1, 18)	5.51	**.03**	(1, 18)	2.37	.14
Group × congruity	(2, 36)	2.06	.14	(2, 36)	0.32	.73
Session × congruity	(2, 36)	3.90	**.03**	(2, 36)	0.77	.47
Group × session × congruity	(2, 36)	4.97	**.01**	(2, 36)	3.85	**.03**
Between subjects analysis (S_1 and S_2 separately)						
Group						
Pre	(1, 18)	21.93	**.001**	(1, 18)	11.62	**.003**
Post	(1, 18)	15.21	**.001**	(1, 18)	6.79	**.02**
Congruity						
Pre	(2, 36)	11.91	**.001**	(2, 36)	11.58	**.001**
Post	(2, 36)	115.41	**.001**	(2, 36)	31.55	**.001**
Group × congruity						
Pre	(2, 36)	3.99	**.03**	(2, 36)	.79	.46
Post	(2, 36)	2.01	.15	(2, 36)	4.98	**.01**

Oz, Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fc5, Fc1, Fc2, Fc6, Cp5, Cp1, Cp2, Cp6). These recording sites plus an electrode placed on the right mastoid were referenced to the left mastoid electrode. Impedances of the electrodes were kept below 5 kΩ. In order to detect eye movements and blinks, the horizontal electrooculogram (EOG) was recorded from electrodes placed 1 cm to the left and right of the external canthi, and the vertical EOG was recorded from an electrode beneath the right eye, referenced to the left mastoid. The data was then re-referenced offline to the algebraic average of the left and right mastoids. Trials containing ocular artefacts, movement artefacts, or amplifier saturation were excluded from the averaged ERP waveforms (average percentage of rejected trials = 13%). The EEG and EOG were amplified by a SA Instrumentation amplifier with a bandpass of .01–30 Hz, and were digitised at 250 Hz by a PC-compatible microcomputer.

2.5. *Data analysis*

Electrophysiological data were analysed for correct responses only using BrainVision Analyser software (version 01/04/2002; Brain Products Gmbh), by computing the mean amplitude in selected latency bands: 0–200, 200–700 and 700–1200 ms, relative to a 150 ms baseline. These latency bands were chosen (1) based upon visual inspection of the waveforms, (2) from results of preliminary analysis in successive 50 ms latency bands and (3) from previous results in the literature (Magne et al., 2006; Moreno & Besson, 2006). Analyses of variance (ANOVAs) were used for all statistical tests, and all *p*-values reported below were adjusted with the Greenhouse-Geisser epsilon correction for non-sphericity. The uncorrected degrees of freedom and the probability level after correction are reported. Before training, 51 and 71% of trials were included in the averages for dyslexics and controls, respectively. After training, this percentage was of 63 and 79%, respectively.

Data were analysed, using four-way ANOVAs including Group (dyslexic *versus* control) as a between-subjects factor, and, as within-subjects factors, Session (pre-training *versus* post-training), Congruity (congruous words *versus* weak incongruities *versus* strong incongruities) and Electrodes (Fz, Cz, Pz, Oz) for midline analysis, or Hemisphere (right *versus* left), Anterior–posterior dimension (three regions of interest (ROI): fronto-central, temporal and parieto-temporal) and Electrode (3 for each ROI: F7/F8, F3/F4, Fc5/Fc6 – T3/T4, C3/C4, Cp5/Cp6 – T5/T6, P3/P4, Cp1/Cp2), for lateral analysis1.[2] Tukey tests were used for all post hoc comparisons.

Modified error rates[3] and RTs were analysed using three-way ANOVAs, including Group (dyslexics *versus* controls) as a between-subject factor and Session (pre-training *versus* post-training) and Congruity (congruous words *versus* weak incongruities *versus* strong incongruities) as within-subjects factors.

3. Results

3.1. *Behavioural data*

Table 3 summarizes the behavioural results obtained in the pitch discrimination task. Results revealed that the main effects of group, session and congruity were significant on both the modified error rate and the RTs. Dyslexic children made overall more errors (1.14) and had longer RTs (1329 ms) than controls (.61 and 1098 ms, respectively, see Fig. 2). After training, children were more accurate and faster (.66 and 1163 ms, respectively) than before training (1.09 and 1263 ms, respectively, see Fig. 2). In both groups, children made overall more errors for the weak incongruity (1.47) than for the congruous words (.64, $p < .001$) and the strong incongruity (.52, $p < .001$). The overall RTs were shorter for the strong incongruity (1128 ms), than for the weak incongruity (1263 ms, $p < .001$) and the congruous word (1249 ms, $p < .001$). Most importantly, while dyslexics

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[2] We also computed an ANOVA including all electrodes. Since results revealed significant interactions between Group, Session, Congruity and Electrodes, we present the results of the midline and lateral analyses.

[3] Modified error rates were used to normalize the percentage of errors distribution and were computed using the formula: [2 × ASIN (RACINE (%errors/100))].

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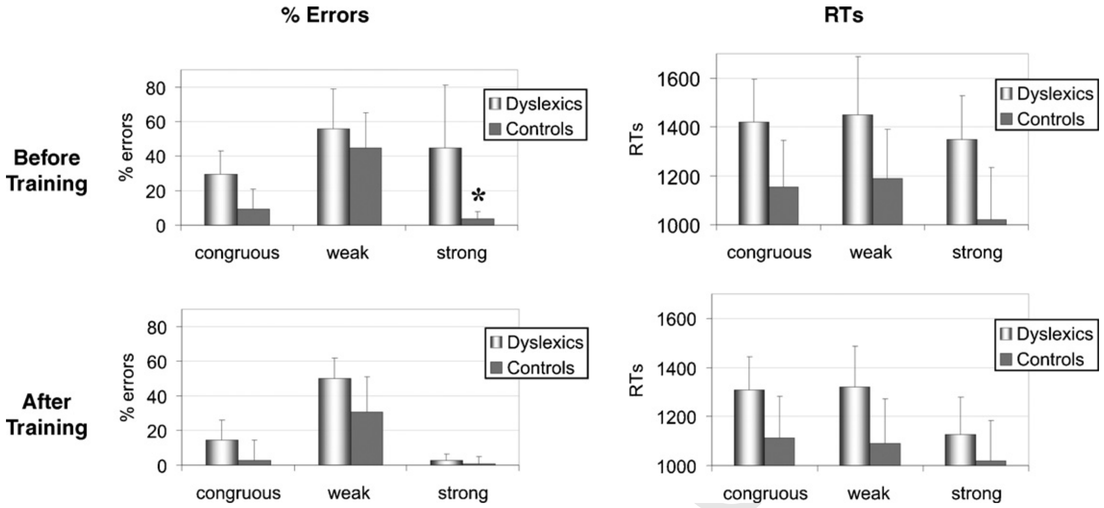

Fig. 2. Percentage of errors and reaction times (RTs) before and after training in the three experimental conditions (congruous words, weak and strong incongruities) for both dyslexic and control children.

made more errors than controls to detect the strong incongruities before training, this difference was no longer significant after training (group × session × congruity).

3.2. *Electrophysiological data*

The effects were not significant in the 0–200 and 700–1200 ms latency bands. By contrast, in the 200–700 ms latency band, the main effect of congruity was significant at both midline and lateral electrodes. Strong incongruities elicited larger positivities (midline: 8.88 µV; laterals: 5.57 µV) than weak incongruities (midline: 4.26 µV, $p < .001$; laterals: 1.23 µV, $p = .02$) and congruous words (midline: 2.64 µV, $p < .001$; laterals: .60 µV, $p = .01$). Moreover, while the main effect of group was not significant, the group by congruity interaction was significant at midline electrodes (see Table 4). Tukey tests showed that for controls, strong incongruities elicited significantly larger positivities (10.55 µV) than weak incongruities (2.70 µV, $p < .001$) and congruous words (1.08 µV, $p < .001$) that did not differ from each other. No such differences were found for dyslexics (strong (7.21 µV) *versus* weak incongruities (5.80 µV, $p = .27$); strong incongruities *versus* congruous words (4.7 µV, $p = .08$)). Finally, the group by session by congruity interaction was also significant.

To further track this interaction, separate pre- and post-training analyses were computed (see Table 4). Results showed that the main effect of group was not significant but the main effect of congruity was significant both before and after training at midline and lateral electrodes. Moreover, the group by congruity interaction was only significant before training at both midline and lateral electrodes. For controls, strong incongruities (midline: 10.31 µV; laterals: 6.38 µV) elicited significantly larger positivities than weak incongruities (midline: 2.32 µV, $p = .05$; laterals: .03 µV, $p = .05$) and congruous words (midline: .53 µV, $p = .01$, laterals: −1.95 µV, $p = .05$, see Fig. 3) that did not differ from one another. No such differences were found for dyslexics either at midline or at lateral electrodes (all $p > .68$; see Fig. 3). Finally, the group by congruity interaction was no longer significant after training (see Table 4), mainly because strong incongruities elicited larger positivities than congruous words not only for controls (midline: 10.78 µV *versus* 1.63 µV, $p < .001$; laterals: 6.55 µV *versus* −1.54 µV, $p = .05$) but also for dyslexics (midline: 8.65 µV *versus* 2.62 µV, $p = .04$; laterals: 6.85 µV *versus* 1.78 µV, $p = .05$) at both midline and lateral electrodes (see Figs. 4 and 5).

3.3. *Reading measures*

Several language and reading tasks were used in the dyslexic group and are presented in Table 2. Performances before and after training were analysed using Student *t*-tests. Most measurements revealed substantial increases in the level of performance after training. Most importantly, the level of performance was significantly higher in the phonological awareness (consonant deletion, auditory acronyms, and rhyme judgement) and spelling tasks after than before training. The increase in the reading tasks was also significant for irregular words and marginally significant for pseudowords.

3.4. *Correlation analysis*

Since the level of performance in the phonological awareness and spelling tasks increased significantly with training, it was of interest to determine whether such increases were correlated with significant increase in the amplitude of the late positivity to strong incongruities. Thus, we computed *Pearson* correlations between behavioural data (level of performance in the reading tests) and electrophysiological data (mean amplitude to strong incongruities at Pz, where the effects were largest) before and after training for the dyslexic children. These analyses revealed no significant correlations before training. Interestingly, however, the correlations were significant after training, for two representative phonological tests: consonant deletion ($r = .67$, $p = .03$) and rhyme judgment ($r = .86$, $p = .001$).

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Table 4
Summary of results (ANOVAs including 3 levels of Congruity) on the mean amplitude in the 200–700 ms latency band

Effect	ANOVAs					
	Midline			Laterals		
	dl	*F*-value	*p*-Value	dl	*F* value	*p*-Value
Between subjects analysis						
Group	(1, 18)	.31	.58	(1, 18)	1.05	.32
Session	(1, 18)	.36	.56	(1, 18)	.1.38	.25
Congruity	(2, 36)	15.73	**.001**	(2, 36)	6.21	**.005**
Group × session	(1, 18)	.01	.94	(1, 18)	1.37	.26
Group × congruity	(2, 36)	5.21	**.01**	(2, 36)	2.39	.11
Session × congruity	(2, 36)	1.00	.38	(2, 36)	2.17	.13
Group × session × congruity	(2, 36)	3.94	**.03**	(2, 36)	3.53	**.04**
Between subjects analysis (pre- and post-training separately)						
Group						
Pre	(1, 18)	.15	.70	(1, 18)	.01	.93
Post	(1, 18)	.20	.66	(1, 18)	1.79	.20
Congruity						
Pre	(2, 36)	4.46	**.02**	(2, 36)	3.55	**.04**
Post	(2, 36)	14.61	**.001**	(2, 36)	5.83	**.006**
Group × congruity						
Pre	(2, 36)	3.52	**.04**	(2, 36)	3.44	**.04**
Post	(2, 36)	2.67	.08	(2, 36)	1.78	.18

4. Discussion

In line with our first hypothesis, analysis of behavioural data revealed that dyslexic children have more difficulties than controls to discriminate pitch manipulations when they are embedded within natural speech. Overall, dyslexic children performed with less accuracy and were slower than controls (see Fig. 2). These results support a general difference between groups, irrespective of stimulus type (no group by condition interaction on RTs or error rates). This pattern of results is particularly striking because the strong incongruity (i.e. a 120% increase in pitch) is very easily detected by control children, as reflected by the low error rate in this condition (see Fig. 2). Thus, these findings are consistent with previ-

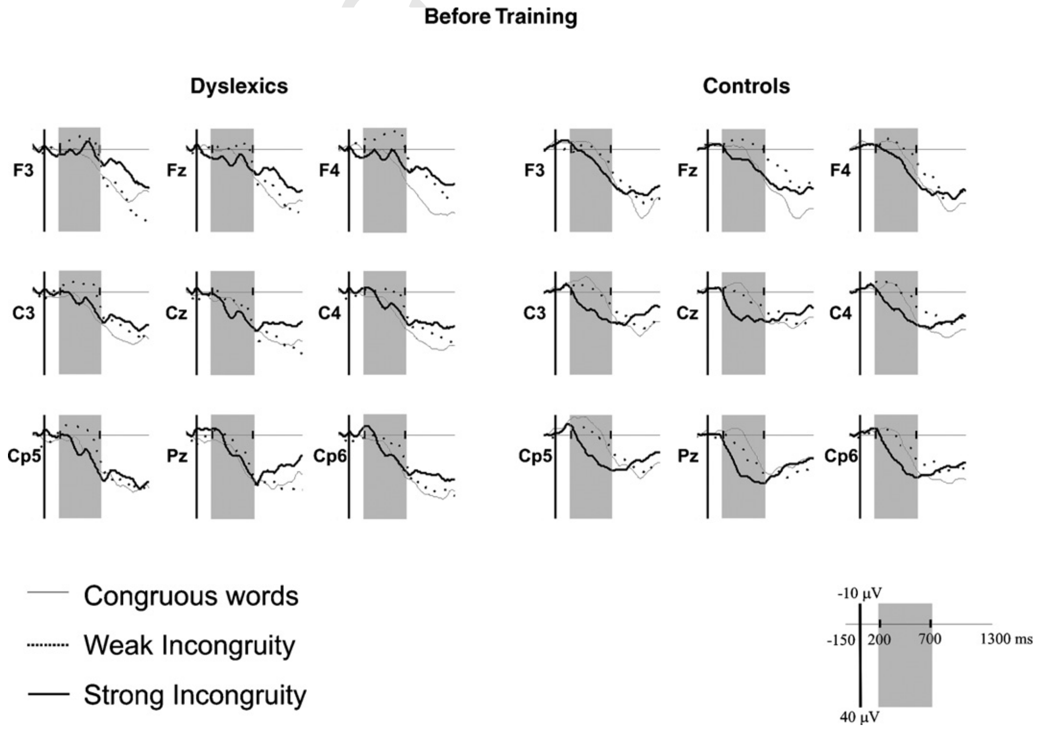

Fig. 3. Illustration of the ERPs elicited by prosodically congruous endings and by weak and strong incongruities in control and dyslexic children before training.

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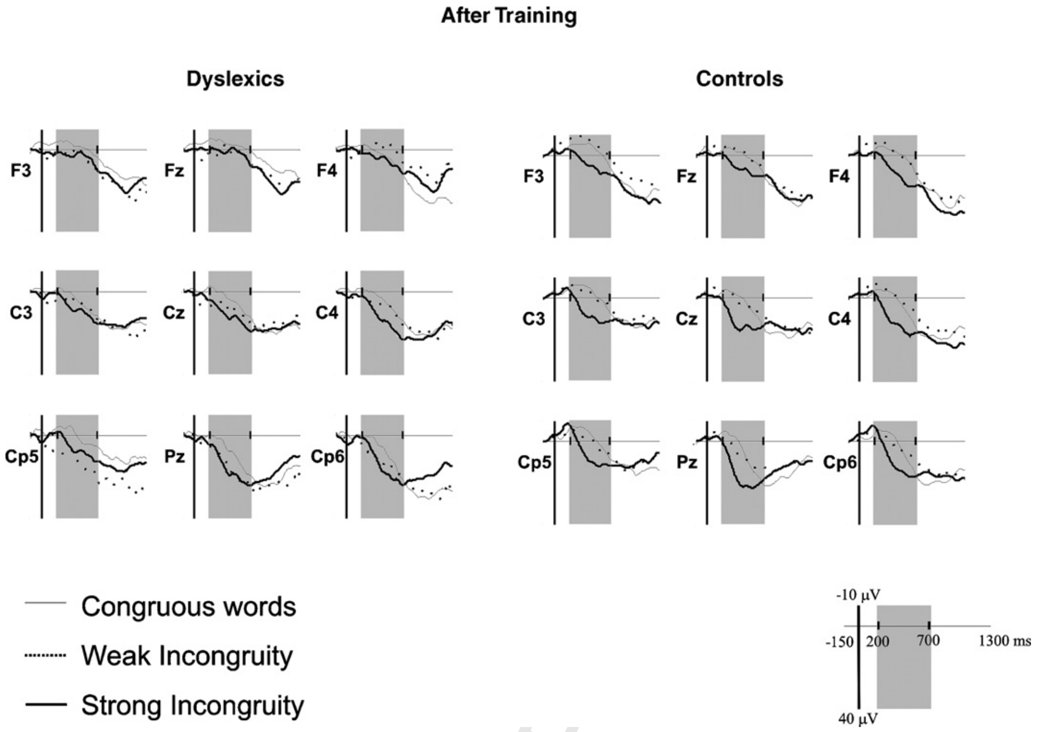

Fig. 4. Illustration of the ERPs elicited by prosodically congruous endings and by weak and strong incongruities in control and dyslexic children after training.

ous ones showing that adult dyslexics (Baldeweg et al., 1999), as well as children at familial risk for dyslexia (Maurer et al., 2003), have more difficulties than controls to detect frequency deviants. Moreover, they are in line with the idea of a covariance between speech prosody and the development of reading skills recently advocated by Foxton et al. (2003).

Interestingly, analysis of the electrophysiological data revealed that, for control children, the amplitude of the late positivity (P300) was larger to strong incongruity than to congruous words before training (see Fig. 3). Precise analysis of the time course of these differences showed that, in line with previous reports with adults (Schön et al., 2004) and children (Magne et al., 2006; Moreno & Besson, 2006), these effects

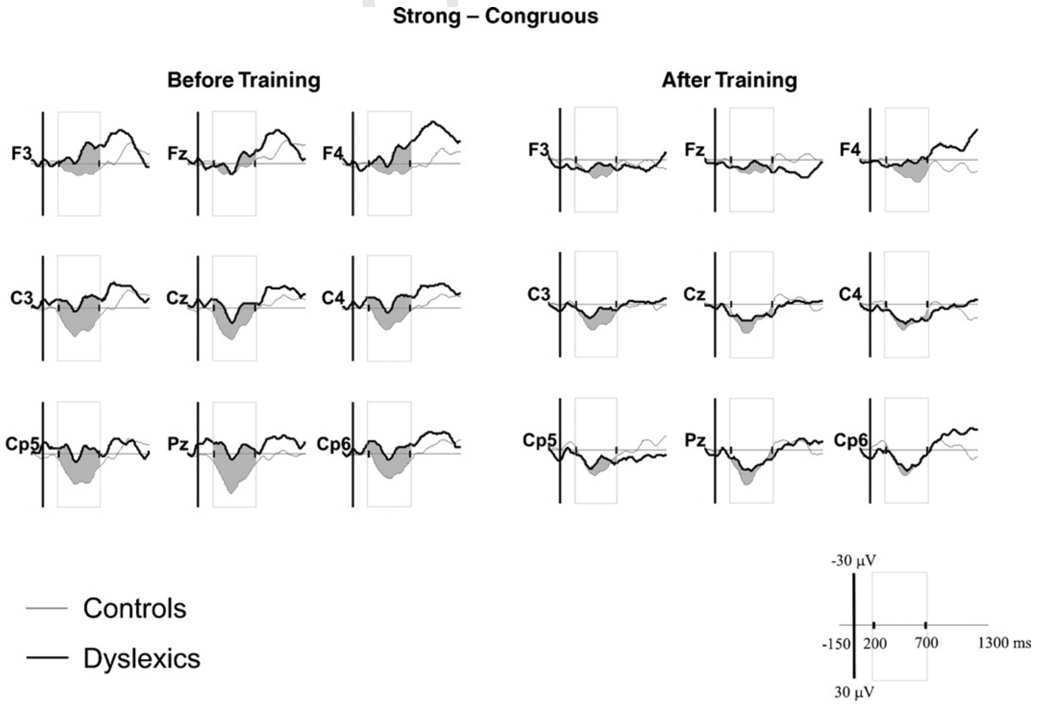

Fig. 5. Difference waves—strong incongruity effect (strong incongruity minus congruous endings) in control and dyslexic children before and after training.

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were localized between 200 and 700 ms. They were interpreted as reflecting the processing of surprising and task relevant events (Duncan-Johnson & Donchin, 1977; Picton, 1992; see Donchin & Coles, 1988, for a review). The amplitude of the evoked responses is thought to depend upon the number of pyramidal cell synapses contributing to postsynaptic potentials (Ponton, Eggermont, Kwong, & Don, 2000). Thus, large neuronal networks may have been activated by the strong pitch deviants, thereby producing large P300 components. By contrast, for dyslexic children, the amplitude of the positivity was not significantly different for strong incongruities and congruous endings before training (see Fig. 3). Based upon the low level of performance of the dyslexics in the detection of the strong incongruity, and on the interpretation of ERP mean amplitude differences above, it may be that only small neural networks were activated by the pitch deviants, and that the amplitude of the positivity to strong incongruities was consequently smaller for dyslexics than for controls. Thus, results with dyslexic children are in line with the interpretation proposed by Kujala et al. (2000, p. 265) that “dyslexic adults have problems discriminating temporal sound features that are surrounded by other sounds”, as is typically the case in natural speech.

It is also interesting to note that results did not reveal any significant differences between controls and dyslexics in the 0–200 ms latency band. Thus, the sensory and perceptual stages of information processing, typically reflected by the exogenous N1-P2 complex (Picton and Hillyard, 1974), do not seem to be impaired in these children. This may be taken to contrast with results of previous MMN experiments suggesting early (preattentive) impairments of auditory processing in dyslexics (Kujala et al., 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001). However, the stimuli used in MMN experiments are usually simpler than in the present study, and the design of the experiments, aimed at testing pre-attentive processing, is quite different from the explicit task used here. Moreover, N1-P2 components are generally difficult to analyze in response to continuous speech because of overlap problems.

Turning to the second aim of this experiment, we now consider the effects of training. In contrast to similar work in the literature investigating neural consequences of intervention in dyslexia, here we compared the dyslexic group to a normal reading control group, matched on reading age, and receiving non-auditory exercises. By comparing behavioural and ERP data between dyslexic and control children before and after training, it was possible to rule out unspecific effects of maturation (children were 3 months older; Taylor & Pang, 1999), repetition (the same sentences as in Test 1 were repeated in Test 2) and familiarity with the procedure and the laboratory environment, that are known to exert large influences on the ERPs (Besson, Kutas, & Van Petten, 1992; Molfese & Molfese, 1997). Interestingly, specific improvements were found for dyslexic children. After training, dyslexics were clearly better at detecting the strong incongruities than before training, thus reaching the same level of performance as controls (see Fig. 2). Consequently, group differences found before training were no longer significant after training. These results suggest that training had a beneficial effect on the pitch discrimination deficit observed before intervention.

This tentative conclusion is supported by the ERP data. While before training, strong incongruities elicited larger positivities than congruous words for controls but not for dyslexics (see Fig. 3), this incongruity effect became significant for dyslexics after training (see Fig. 4). In line with the interpretation of the amplitude of the evoked responses proposed above, it may be that remedial training, by increasing sensitivity to pitch, did increase the size or the efficiency of the neural networks involved in the detection task and consequently, was associated with an increase in P300 amplitude. Most importantly, such an increase is clearly in line with previous ERP studies suggesting that the P300 component is particularly sensitive to changes in cognitive processes following learning (Johnson et al., 1985; Key et al., 2006; Paller et al., 1987; Rose et al., 2001). To summarize, results on error rates, RTs and ERPs converged to show that, before training, dyslexics were impaired compared to controls at discriminating strong deviations of pitch and that these differences were diminished after training (see Fig. 5).

Dyslexics also showed improvements on standardised reading measures (phonological awareness and spelling tasks) after the training intervention. Thus, these post-intervention results are consistent with previous reports showing that daily intensive phonological training significantly improves most phonological and some written-language variables (Foorman et al., 1997; Habib et al., 1999, 2002; Hatcher, Hulme, & Ellis, 1994; Lovett et al., 1994; Olson, Wise, Ring, & Johnson, 1997; Torgesen, Wagner, Rashotte, Alexander, & Conway, 1997; Torgesen et al., 2001; Wise & Olson, 1995).

Overall, our findings of impaired pitch detection improved by specific phonic intervention, as well as ERP evidence for brain plasticity demonstrated by the normalization of late potentials in the 200–700 ms window (see Fig. 5), suggest that impaired pitch processing within natural speech, although probably not the unique reason, may contribute to deficient phonological representations in dyslexics that may, in turn, led to an impaired development of reading skills. This interpretation is supported by the finding of significant correlations between the amplitude of the late positivity at central parietal sites, where learning effects are typically larger (Holamon, Morris, & Retzlaff, 1995), and the level of performance in the phonological awareness tests. While interesting, this interpretation, and in particular, the nature of the relationship between pitch processing and reading abilities, need to be further examined in future experiments. If we are correct in supposing a link between pitch processing and reading abilities through phonological representations, it would be interesting to test the effect of musical training. Indeed, by increasing the sensitivity to pitch, musical training may have beneficial effects on reading skills, while still offering the advantage of focusing the remediation on other aspects than language.

In conclusion, the findings of the current study suggest that deficits in pitch processing, in particular when stimuli are embedded into larger speech units, should be added to the deficits uncovered by previous research, in particular deficits of the temporal processing of speech components (Giraud et al., 2005). Also, our results are promising as they suggest that children

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with developmental dyslexia are not only trainable, as indicated by improvement in the level of reading performance, but also that specific training can be associated with noticeable changes in brain's response to pitch manipulations. Furthermore, these results suggest that electrophysiological responses underlying specific language processes in dyslexic children can be modified to closely resemble those of normal readers, at least when remedial programs are built upon coherent and theory-based principles and applied in intensive training periods. The effect of phonic intervention could be, as suggested by the normalization of ERPs after training, to "rewire" (Habib, 2003) misconnected circuits involved in integrating the elementary features of the auditory signal into more complex and sophisticated speech units. Thus, ERPs clearly appear as a valuable tool, both uninvasive and highly sensitive, to be used in future investigations on intervention efficacy in dyslexia.

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