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Phonological processing in dyslexic children: a study combining functional imaging and event related potentials

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Abstract

Difficulties in phonological processing are currently considered one of the major causes for dyslexia. Nine dyslexic children and eight control children were investigated using functional magnetic resonance imaging (fMRI) during non-oral reading of German words. All subjects silently read words and pronounceable non-words in an event related potentials (ERP) investigation, as well. The fMRI showed a significant difference in the activation in the left inferior frontal gyrus between the dyslexic and control groups, resulting from a hyperactivation in the dyslexics. The ERP scalp distribution showed a significant distinction between the two groups concerning the topographic difference for left frontal electrodes in a time window 250–600 ms after stimulus onset for non-word reading. Both the fMRI and the ERP results support differences in phonological processing between dyslexic and normal-reading children.

Keywords: Developmental dyslexia; Phonological processing; Children; Functional magnetic resonance imaging; Event related potential; Broca's area; Reading; P3

The present study is based on the phonological deficit hypothesis of dyslexia [18]. It is known that reading acquisition critically involves the segmentation of text into graphemes. Graphemes are related to phonemes, and grapheme-phoneme-conversions are then related to the whole sound of the word [2]. This involves both assembled (piecemeal) and addressed (whole-word) phonology. According to the phonological deficit hypothesis of dyslexia, all these steps are particularly problematic for dyslexics and cause an atypical development of reading skills.

In neuroimaging studies, abnormalities of activation in the perisylvian structures and the posterior temporoparietal brain areas of the left hemisphere have been associated with impaired phonological processing in developmental dyslexia [3,7,10,14,17]. Some authors [4,23] have attempted to use the high time resolution of Event Related Potentials (ERP) to investigate the problem of which region is activated first, or the order in which various brain regions are involved in reading tasks. The first findings [5,19] suggest a correlation in the measurement of blood flow changes – functional Magnetic Resonance Imaging (fMRI) and the measurement of electric activity – ERP concerning the differentially active brain regions in particular reading tasks. A spatial comparison of fMRI and ERP-topography allows conclusions to be drawn from the ERP data about the timing of the activation in these regions. For example, Posner et al. [11] using data on eye-fixation times taken from normal-reading studies as well as positron emission tomography and ERP-studies, have constructed a time line for processing during word reading.

For these reasons we have merged two separately conducted studies (fMRI and ERP) on the same subjects, using similar reading tasks, assuming that group differences between the dyslexic and control children in reading tasks (concerning spatial resolution of fMRI and the time-window of ERP-topography) will help to delineate a possible cerebral representation of the phonological deficit.

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Table 1
Demographic and behavioural data

Subjects in fMRI and EEG	Dyslexic children	Control children	Significance (*P*)
N	9	8	
Age	12.6	12.7	0.933
Intelligence	105.3	96.0	0.127
Writing test –IQ	71.4	94.9	0.003
Reading test-IQ	85.1	105.0	0.033
Word-reading			
1 syllable time (s)	1.47	0.57	0.037
Errors (%)	9.67	0.93	0.150
3 syllables time (s)	2.94	1.14	0.057
Errors (%)	14.67	4.73	0.123
Non-word-reading			
1 syllable time (s)	2.28	0.90	0.016
Errors (%)	18.20	14.27	0.693
3 syllables time (s)	5.12	2.38	0.051
Errors (%)	40.00	16.20	0.016
Letter Transformation			
1 syllable time (s)	5.38	3.72	0.045
Errors (%)	15.85	7.85	0.291

17 subjects with a mean age of 13 years (nine dyslexic and eight control boys matched for age and intelligence) took part in the experiment (see Table 1). All subjects included in the study were right-handed (assessed by a standardized handedness test) [22], and had a normal non-verbal intelligence (IQ $>$ 85) [13]. The control children showed a normal-reading and spelling performance according to standardized reading and spelling tests for the German language [12]. The dyslexic children were diagnosed based on the discrepancy between non-verbal IQ and reading/spelling performance (for details see [7]).

In a behavioural experiment done prior to the fMRI and ERP investigations the following stimuli were used: (a) nouns characteristic of the basic vocabulary of 10 year old children (two word lengths: 1 syllable and 3 syllables); (b) pronounceable non-words (also two lengths), which followed the rules of German phonology and orthography (e.g. 'Bnams'); and (c) asterisks ('baseline-condition'). In the behavioural task the subjects read the stimuli aloud; reading times and errors were assessed (see Table 1).

In both the fMRI and ERP studies the subjects silently read the same type of linguistic stimuli. Each stimulus was presented as one per 2000 ms on the screen and remained visible for 1800 ms for the task (silent reading) as well as for the control condition (asterisks). A block fMRI design was used. The task condition contained four blocks of word reading that were alternated by four blocks that required the subjects to look at three asterisks (control condition). Each experiment consisted of a total of eight blocks always starting with the control condition. The total duration of the experiment was 20 min, with each block lasting for 2.5 min (75 stimuli per block). Five images in one slice were acquired per block which amounted to 40 images altogether. The ERP's were measured in a separate session. The stimuli (100 words, 100 non-words with a comparable length) and the control condition (asterisks) were presented in a pseudorandomized order in one session.

For the fMRI, the subjects were investigated using a 1.5 T MR scanner (Philips Gyroscan ASCII) with a standard head coil. Functional images were based on a T2* weighted gradient echo sequence with the following parameters: flip angle $= 40°$, TE $= 50$ ms, TR $= 100$ ms, matrix: 256×152, non-square field of view of 230×161 mm, slice thickness $= 10$ mm. Images were obtained in one slice 2–12 mm above and parallel to the line between the anterior commissure (AC) and the posterior commissure (PC) [21]. The EEG was recorded by using 24 Ag/AgCl scalp electrodes placed according to the international 10/20 system (including Fpz and Oz) referred to linked mastoids. ERPs were sampled with 51 Hz. The electrode impedance was kept below 5 kΩ. The EEG and electrooculogram were low-pass filtered (0–30 Hz).

fMRI data were analyzed by Statistical Parametric Mapping (SPM 96) [20]. The following steps were performed: realignment with reference to the first scan using a least square approach; fitting into a standard space [20,21] by means of a 2D affine transformation; smoothing with a 6 mm full width at half maximum isotropic kernel for group analysis. The design matrix was specified with global activity as a confounding covariate. Separate SPMs (computed as a contrast of task versus control condition) were computed for dyslexics and for the normal-readers. In addition, the group x condition interaction was used to compute the differences between dyslexics and normal-readers (see Fig. 1). The resulting SPM{Z} were thresholded at $P = 0.05$ for height (u) and uncorrected $P = 0.05$ for the spatial extent (k). SPM{Z} maps were superimposed on an average anatomical scan, which was created from the corresponding anatomical scans of all children included in the study. For the ERPs, we rejected trials with voltage exceeding ± 100 μV. The remaining trials were corrected for baseline over a 100 ms window prior to the stimulus onset, and were averaged in synchrony with the stimulus onset separately for each stimulus type, over an analysis period of 2000 ms. 2D maps of scalp voltage were constructed by spherical spline interpolation implemented in the software Scan (Neuroscan, inc.). The groups of dyslexic and normal-reading children were compared with respect to scalp voltage using sample-by-sample *t*-tests ($P < 0.05$) for five consecutive samples on 19 electrodes simultaneously (100–180 ms, 180–250 ms, 250–350 ms, 350–500 ms, 500–600 ms).

The results of fMRI-analysis are shown in Fig. 1.

For the control group we obtained a significant activation (words minus asterisks) only in the left inferior frontal gyrus (IFG) (corresponding with the Brodman area (BA) 44). The dyslexic children showed three areas of activations: (1) in a cluster including the left IFG, the left insula and the anterior part of the left temporal superior gyrus; (2) in a posterior

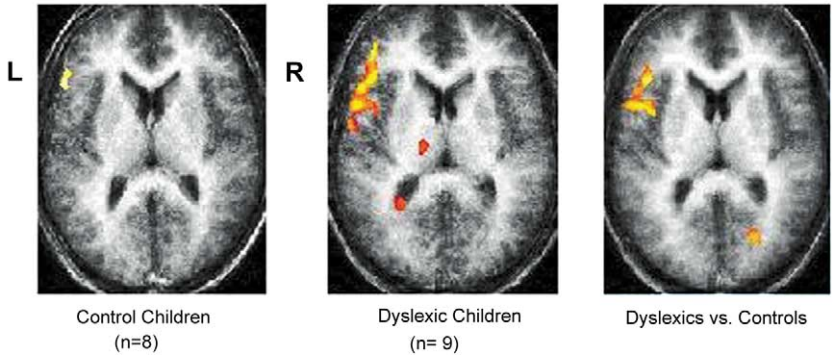

Fig. 1. The statistical parametric maps showing activated voxels in a horizontal slice (2–12 mm parallel to the bicommissural (AC-PC) line [21]). Silent reading in comparison with fixation points for the normal-reading children (left) and dyslexic children (middle), group differences between dyslexics and controls (right). ($P < 0.05$).

part of the left thalamus; and (3) in a part of the nucleus caudatus left. The group analysis showed significant hyperactivation in Broca's area (BA 44), the anterior insula and in the lingual gyrus (right temporo-occipital region, BA 18) for dyslexics in comparison to the controls.

The qualitative information about electrical activity measured on the scalp was obtained from spline maps of the scalp potentials (Fig. 2). The time windows were chosen by separating five consecutive different voltage samples. In comparison to the fMRI, in the scalp potentials we have a significant left frontal voltage difference in the time window 250–500 ms. The group difference in this area is significant only for non-words.

For the left frontal electrode position (F3) we illustrated the grand averages for the dyslexic and control group in the non-word reading. The statistical analysis of the non-word reading task for the left frontal electrode (F3) tends to result in significant group differences ($P < 0.1$) for the third and fourth analysis period: 250–350 ms and 350–500 ms (Fig. 3).

According to the fMRI results the reading processes can be attributed to fairly well-defined brain loci.

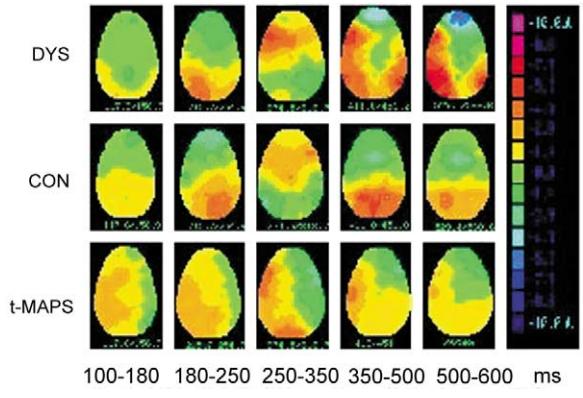

Fig. 2. ERP topography in non-word reading. DYS, scalp voltage on 19 electrodes simultaneously for the group of dyslexic children; CON, for the normal-reading children; t-MAPS, sample-by-sample *t*-tests in five samples with significant *t*-values in red or blue.

Silent word reading, by the control children, causes a significant activation in the IFG (BA 44, Broca's area). This area has been described in many studies as being involved in language processing, particularly when non-words are used [9,15,16] or when phonetic decisions are required [6]. Broca's area is considered to be involved in the phonological coding in lexical identification (piecemeal or assembled phonology).

The behavioural data demonstrate that, solving the phonological decoding tasks (word/non-word reading and letter transformation), was more problematic for the dyslexics (i.e. slower encoding, thereby requiring greater effort). The neuroimaging results in connection with the behavioural data indicate the difficulties in phonological processing in the dyslexic group. The group differences in Broca's area can be clearly attributed to the dyslexic children's difficulties in reading the stimuli. On the basis of the 'phonological' function of this brain region, the hyperactivation of Broca's area in the dyslexics, in comparison to the controls, could reflect an increasing effort concerning phonological coding. Independent from the possible involvement of other additional problems, this brain activation is in line with data supporting a phonological deficit in dyslexia. Ingvar et al. [8] described the overactivation of

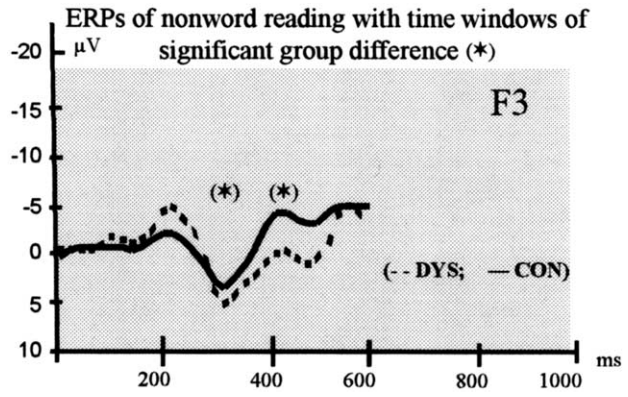

Fig. 3. Non-word-related potentials for dyslexic and control children (left frontal, Electrode: F3).

dyslexics in an oral reading task as a result of the increased complexity of the task. Furthermore, this agrees with other recent studies [3,17], where the increasing involvement of Broca's area in groups of dyslexic adults is regarded as a compensation for the reduced efficiency in sublexical translations or lexical retrieval.

As the fMRI analysis indicated differential activation of the brain between the dyslexic and normal groups, we also expected to find, over the same areas, group differences in the scalp topography of the ERP recording array. In the nonword reading task, with increasing demand on phonological encoding, the left frontal spatial group-difference in ERP shows similarities to the results of the fMRI group-analysis and provides a time window that can be seen as related to phonological processes. According to Posner's time line of word reading [11], the time window of 250–500 ms, (where the biggest differences between the two groups are found in the left brain region), is related to phonologic and lexical encoding. In this time window, a positive ERP-component (P3) is more accentuated in the group of dyslexic children when compared with the control group. This P3 is seen as reflecting the task complexity and/or the level of processing induced by each task [1].

A few limitations to this study should be noted: i.e. the single-slice technique (fMRI); the spatial comparison of fMRI and ERP without source localizations; and the small sample size. However the comparison of the fMRI and ERP data is done in our study on the same group of subjects. By the spatial comparison of the two sets of data which demonstrate the group differences as seen in the left IFG, as well as the ERP data which show the group differences in a time window strongly associated with phonological processing, we have significantly strengthened the phonological deficit hypothesis of dyslexia.

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