

# Dissociation of Normal Feature Analysis and Deficient Processing of Letter-strings in Dyslexic Adults

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**Neuroimaging studies have revealed that the functional organization of reading differs between developmentally dyslexic and non-impaired individuals. However, it is not clear how early in the reading process the differences between fluent and dyslexic readers start to emerge. We studied cortical activity of ten dyslexic adults using magnetoencephalography (MEG), as they silently read words or viewed symbol-strings which were clearly visible or degraded with Gaussian noise. This method has previously been used to dissociate between analysis of local features and pre-lexical word processing in fluent adult readers. Signals peaking around 100 ms after stimulus onset and originating in the postero-medial extrastriate cortex were associated with increasing local luminance contrast in the noise patches. These early visual responses were similar in dyslexic and non-impaired readers. In contrast, the letter-string-specific responses peaking around 150 ms predominantly in the left inferior occipito-temporal cortex in fluent readers were undetectable in dyslexic readers. Thus, while the early visual processing seems intact in dyslexic adults, the pattern of cortical activation starts to differ from that of fluent readers at the point where letter-string-specific signals first emerge during reading.**

## Introduction

Developmental dyslexia is characterized by difficulties in learning to read and write in the absence of gross neurological pathology. There is convincing evidence that abnormal phonological processing contributes to poor reading (Lundberg *et al.*, 1980; Bradley and Bryant, 1983; Wagner and Torgesen, 1987; Shankweiler *et al.*, 1995; Muter *et al.*, 1997), but visual abnormalities, especially in magnocellular functioning, are also commonly reported (Lovegrove *et al.*, 1986; Livingstone *et al.*, 1991; Cornelissen *et al.*, 1995; Stein and Walsh, 1997; Demb *et al.*, 1998). Poor phonological awareness is manifested as difficulties in understanding and utilizing the relationship between the letters of the written word and the phonological structure of the corresponding spoken word (Frith, 1985). Consequently, single-word reading is inaccurate and slow, especially when recognition of a word requires fluent letter-to-sound conversion, like when reading pseudowords (Rack *et al.*, 1992; Wimmer, 1993; Landerl *et al.*, 1997). Reading continues to be slow and error prone in dyslexic individuals also in adulthood (Scarborough, 1984). Thus, it is not surprising that imaging studies have found activation patterns of various brain regions to differ between non-impaired and dyslexic adults during reading [for reviews, see Flowers (Flowers, 1993) and Rumsey (Rumsey, 1996)].

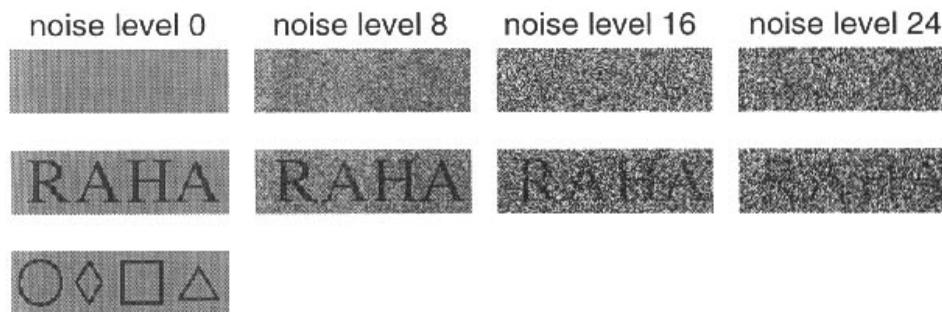
Reading is assumed to proceed through several stages, the exact nature and relative spatiotemporal cortical organization of which are still unsettled. Visual word recognition begins with feature analysis. Thereafter fluent reading has been suggested to continue via serial or parallel analysis of the letters of a word to activation of the whole visual word form from the mental lexicon. Finally word meaning is accessed from the semantic

store (Coltheart, 1978; McClelland, 1987; Monsell, 1987; Coltheart *et al.*, 1993).

Only techniques measuring neural electromagnetic events directly, like electroencephalography (EEG) or magnetoencephalography (MEG), can follow the flow of information in the cortex with millisecond resolution. Unlike electric potentials, magnetic fields penetrate the skull and scalp undistorted. Localization of cortical signals associated even with complex cognitive tasks can thus be accomplished totally non-invasively using MEG. According to MEG and intracranial event-related potential (ERP) recordings, the earliest letter-string-specific responses occur in the inferior occipito-temporal areas within 140–200 ms after stimulus onset (Halgren *et al.*, 1994; Nobre *et al.*, 1994; Tarkiainen *et al.*, 1999). As the signals in the left occipito-temporal area have been reported to be equally strong to words and pseudowords (Salmelin *et al.*, 1996), this early activation probably reflects pre-lexical processing. Around 400 ms after word onset, scalp-recorded ERPs are sensitive to the semantic appropriateness of a word in sentence context (Kutas and Hillyard, 1980). According to MEG measurements, written word and sentence comprehension recruits neuronal populations predominantly in the left superior temporal cortex between 250 and 600 ms after word onset in fluent readers (Helenius *et al.*, 1998).

Several studies have reported differences between fluent and dyslexic readers in the ERPs around 400 ms after word presentation (Stelmack *et al.*, 1988; Stelmack and Miles, 1990; Brandeis *et al.*, 1994). Further, in a recent MEG study the beginning of responses reflecting semantic analysis of inappropriate sentence-final words was delayed in dyslexic individuals, thus indicating problems already in the preceding stages (Helenius *et al.*, 1999). This finding is in agreement with earlier results of Salmelin *et al.* (Salmelin *et al.*, 1996) who discovered that while in fluent readers the left occipito-temporal area was activated around 180 ms after presentation of isolated words and pseudowords, this area remained silent or was activated much later in dyslexic adults. Only one study has looked specifically at the early visual responses evoked during reading in dyslexic subjects. ERPs around 100 ms after word onset were abnormally weak in dyslexic children during reading (Brandeis *et al.*, 1994), but as localization of the responses was not attempted the full nature of these differences is unknown.

In a recent MEG study of early processes of reading, Tarkiainen *et al.* (Tarkiainen *et al.*, 1999) succeeded in dissociating visual feature analysis and letter-string-specific processing in fluent adult readers in both space and time. The stimuli consisted of words, syllables and letters as well as equally long symbol-strings which were presented on a grey background or were degraded by variable addition of Gaussian noise. Activation in the postero-medial extrastriate areas around 100 ms after stimulus onset increased with increasing noise levels, i.e. with



**Figure 1.** The stimuli used in the study were Gaussian noise patches (upper row, noise levels 0–24), common four-letter nouns (middle row, noise levels 0–24) and four-item symbol-strings (lower row, noise level 0).

increasing local luminance contrasts in the image, suggesting involvement in visual feature analysis. A totally different pattern of activation was detected in the left occipito-temporal area, where activation was delayed or decreased with increasing noise level, i.e. with decreasing visibility of the word, around 150 ms after word onset. Further, this lateral occipital area displayed clear letter-string preference since activation elicited by equally long symbol-strings was significantly delayed or was weaker compared with that for words or syllables. In the present study the same words and symbol-strings were used as stimuli to elucidate the functional organization of early stages of visual word recognition in dyslexic subjects.

## Materials and Methods

### Subjects

We studied ten adults with a history of developmental dyslexia (four females, six males; age 22–36 years, mean 30 years). These individuals had been diagnosed during school years by a psychologist, a speech therapist or a specialist teacher. All subjects had finished the minimum of 2 years of formal education following comprehensive school (9 years in Finland), indicating that their reading problems were not due to inferior intellectual capacity. There was a family history of reading problems in six cases (affected parent or sibling). One of the dyslexic subjects was left-handed. Dyslexic subjects were tested with a concise behavioural test battery consisting of verbal working memory, naming and reading tasks known to be sensitive for dyslexia (Denckla and Rudel, 1976; Jorm, 1983; Scarborough, 1984; Wolf, 1986; Wolf and Obregon, 1992; Korhonen, 1995).

As a group, the dyslexics performed significantly worse than 20 age-matched control subjects in these behavioural tasks [ $F(1,27) = 37.1$ ,  $P < 0.0001$ ]. Planned contrasts revealed statistically significant differences between groups in digit span forwards ( $5.4 \pm 0.4$  in dyslexic and  $6.4 \pm 0.2$  in control subjects; mean  $\pm$  SEM,  $P < 0.04$ ) and backwards ( $4.3 \pm 0.5$  and  $5.7 \pm 0.4$ ,  $P < 0.03$ ) (Wechsler, 1955). Also naming speed of both colours ( $648 \pm 29$  and  $472 \pm 28$  ms/item,  $P < 0.0001$ ), and colours, digits and numbers ( $701 \pm 37$  and  $532 \pm 19$  ms,  $P < 0.0001$ ) presented in a matrix was slower in dyslexic compared with control subjects, as well as the oral reading speed of a narrative ( $671 \pm 52$  and  $391 \pm 10$  ms/word,  $P < 0.0001$ ). The dyslexic subjects were also markedly slow in detecting real Finnish words in a computerized lexical decision task compared with control group ( $1202 \pm 192$  and  $554 \pm 22$  ms,  $P < 0.0001$ ). In each dyslexic individual either the oral reading or word recognition speed was at least two standard deviations slower than the mean of the control group.

The MEG data from 12 normal right-handed subjects (four females, eight males; age 21–42 years, mean 29 years), reported independently by Tarkiainen *et al.* (Tarkiainen *et al.*, 1999), are the basis for the following comparisons between dyslexic and control subjects. Anatomical magnetic resonance (MR) images were available for all control and three dyslexic subjects. Informed consent was obtained from all subjects.

### Stimuli in the MEG experiment

The stimuli comprised Gaussian noise patches (noise levels 0, 8, 16, 24),

dark grey words presented in variable Gaussian noise (noise levels 0, 8, 16, 24), or symbol-strings (noise level 0) (see Fig. 1). The size of the noise patches was  $5^\circ \times 2^\circ$ . In the noise level 0 the patches were evenly grey. When noise was added, the luminance of each pixel was allowed to vary along the black-to-white scale at three probability levels (noise levels 8, 16, 24). Different noise levels in stimulus images were obtained by changing the grey level value of each pixel randomly. The amount of change was picked from a Gaussian distribution with zero mean and standard deviation corresponding to the applied noise level (8, 16, 24). If the new grey level value fell outside the possible range 0–63, the procedure was repeated for that pixel. Effectively this manipulation increased the local luminance contrast in the noise patches with increasing noise level, although the overall luminance remained essentially constant.

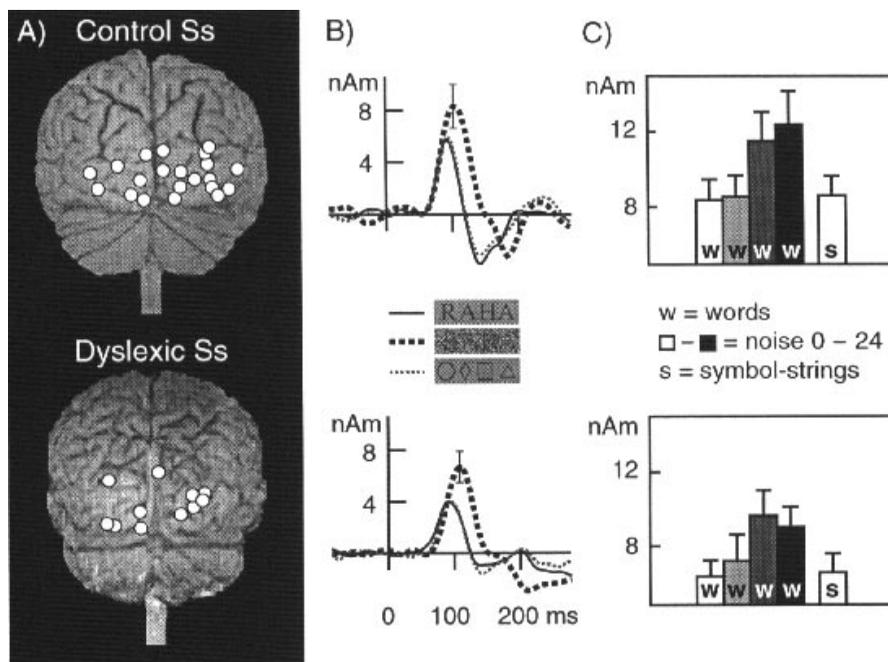
When words were embedded in the noise the pixels of both words and backgrounds were allowed to vary in luminance. In the moderate noise levels (8 and 16) the words were still rather easily detectable, but in the heaviest noise level (24) mostly undetectable. We used 50 different common Finnish nouns. The symbol-strings were composed of a triangle, a square, a circle and a diamond, the relative positions of which were varied to produce a total of four different symbol-strings. All images were shown on a large background of uniform grey. The grey level of the background was set to 150 (on a scale of 0–255 from black to white), based on the mean level of the different stimuli. A detailed description of the stimuli can be found in Tarkiainen *et al.* (Tarkiainen *et al.*, 1999).

### Procedure in the MEG experiment

Measurements were conducted in a magnetically shielded room. The stimuli were projected on a screen at a distance of about 1 m from the subject. The stimuli were presented once every 2 s and the display duration was 60 ms. Each subject was studied during a single day in two 20–30 min sessions separated by a break. During one session subjects were shown words (noise levels 0–24) or symbol-strings (noise level 0). In the other session only noise patches (noise levels 0–24) were presented. The order of the two sessions was alternated between successive subjects. Within sessions the order of the noise levels was randomized. Moreover, we ensured that, in the session including words, the same word was not repeated within 30 s to minimize repetition effects. Subjects were asked to pay attention to the stimuli and in the word session they were instructed to say aloud the word they had just seen when prompted by a question mark (1.5 % probability).

### MEG Recordings and Analysis

MEG detects magnetic fields associated with synchronous activation of thousands of nerve cells, non-invasively outside of the head. The main contribution to MEG signals arises from the fissural cortex (Hämäläinen *et al.*, 1993). The MEG measurements in the present study were conducted using the Neuromag-122™ whole head system (Ahonen *et al.*, 1993). Neuromagnetic signals were averaged on-line from 200 ms before stimulus presentation to 800 ms after. Signals were bandpass filtered to 0.03–120 Hz and sampled at 0.4 kHz. Both horizontal and vertical eye movements were recorded on-line (bandpass 0.03–100 Hz) and epochs contaminated by eye or lid movements were rejected. For each stimulus category, at least 70 artefact-free responses were gathered.



**Figure 2.** (A) Sources related to visual feature analysis across control (upper row) and dyslexic subjects (lower row). (B) Mean time behaviour of the sources involved in visual feature analysis in control (upper curves) and dyslexic subjects (lower curves). Responses to the non-degraded words (solid black lines) and symbol-strings (grey dotted lines) are smaller in amplitude than responses ( $\pm$  SEM) to the most heavily degraded words (black dotted lines). (C) The mean strength ( $\pm$  SEM) of all sources related to visual feature analysis in control (upper histogram) and dyslexic subjects (lower histogram).

Individually for each subject, the neuromagnetic signals detected by the 122 channels were reduced into time behaviour of distinct brain areas using equivalent current dipole (ECD) analysis (Hämäläinen *et al.*, 1993). ECD represents the centre and strength of activation in a given brain area and the orientation of current flow therein. The magnetic field patterns were visually inspected to identify local dipolar fields that were not distorted by simultaneous activation in nearby cortical areas. Isolated dipoles were calculated from signals in those channels that covered the field pattern. Thereafter, all individually determined dipoles (on average 10 in both control and dyslexic subjects) were incorporated into a multidipole model. Dipole locations and orientations were fixed, but their strengths were allowed to vary in time in order to achieve optimal fit to the measured signals. To focus on the early reading related activation, multidipole modelling was carried out for the first 300 ms after stimulus onset using only the dipoles predominantly active during this period. Analysis was conducted using a spherical head model emphasizing best agreement with the shape of the skull over the occipital areas. In a separate modelling all localized dipoles were used to explain data for the whole averaging period. In this analysis we used a head model with the best description of the skull curvature over the temporal areas. In those seven dyslexics for whom magnetic resonance images (MRIs) were not available we used average head models derived from female and male brains. The locations of three head position indicator coils attached to the subject's head were determined with respect to the measurement helmet in the beginning of the session. The location of these coils with respect to nasion and reference points anterior to ear canals was further used to align functional MEG and anatomical MRI data.

#### Detection of Activation Related to Visual Feature and Letter-string Analysis

Based on the criterion used in Tarkiainen *et al.* (Tarkiainen *et al.*, 1999), a dipole was judged to be involved in visual feature analysis if its strength systematically increased with noise level (noise level  $0 \leq$  noise level  $8 \leq$  noise level  $16 \leq$  noise level  $24$ ) in the condition where noise patches were shown without embedded words/symbols. We required that the peak activation was statistically significantly stronger for the patches with highest level (24) of Gaussian noise than for patches with zero level of noise (evenly grey patches), i.e. the difference had to exceed 1.96 times

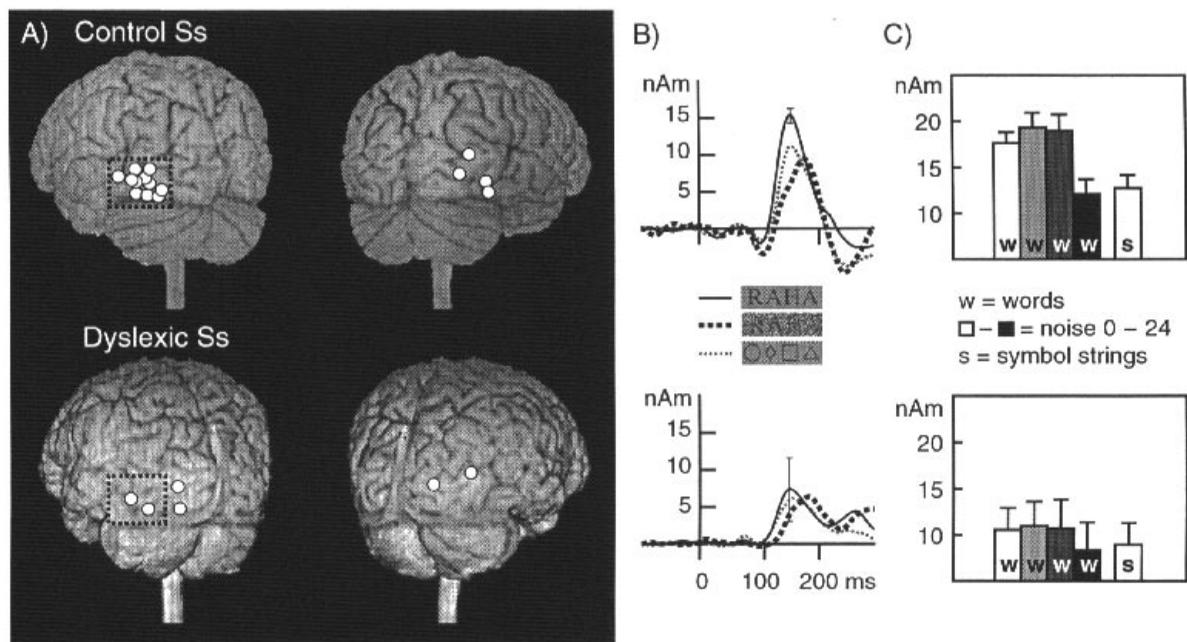
the standard deviation in the pre-stimulus period ( $-200$  ms to stimulus onset). In the study by Tarkiainen *et al.* (Tarkiainen *et al.*, 1999) only the most robust sources were reported – sources that displayed statistically significant differences already between noise levels 0 and 8.

The same criteria as in Tarkiainen *et al.* (Tarkiainen *et al.*, 1999) were used for determining whether dipole activity reflected preference to letter-string stimuli. Firstly, only those sources were accepted which showed either significantly stronger or earlier response to words than to symbol-strings. This condition was fulfilled if the peak response was either statistically significantly stronger to non-degraded words (noise 0) than to symbol-strings, i.e. the difference exceeded 1.96 times the standard deviation in the pre-stimulus period ( $-200$  ms to stimulus onset), or if the peak latency of the response to the symbol-strings was delayed with respect to non-degraded words by at least 5 ms (twice the minimum time resolution defined by the sampling rate). Secondly, peak activation had to be reduced for the most degraded words or systematically delayed as the words became harder to recognize, i.e. peak response was either statistically significantly stronger to non-degraded words (noise 0) than to the most heavily degraded words (noise 24), or the peak latency of the response to the most degraded words was delayed with respect to non-degraded words by at least 5 ms. If the latency criterion was used, the response amplitude to the most degraded words was still not allowed to exceed that to non-degraded words.

## Results

### Activation Associated with Visual Feature Analysis

Figure 2A displays all the activated brain areas in control and dyslexic subjects that were involved in visual feature analysis up to 130 ms after stimulus presentation. In these source areas the responses to the noisiest patches were significantly stronger than those to the noiseless patches. This activation pattern was detected in nine control subjects (Tarkiainen *et al.*, 1999) and in seven dyslexic subjects. The overall number of feature analysis sources was 21 in control and 11 in dyslexic subjects. On average dyslexic subjects had 1.1 and control subjects 1.8 sources



**Figure 3.** (A) Sources preferentially activated by letter-string stimuli up to 180 ms after word presentation in control (upper row) and dyslexic subjects (lower row). In control subjects the responses were strongly lateralized to the left inferior occipito-temporal cortex (dashed rectangle). (B) The mean time behaviour of the letter-string-specific sources in control (upper curves) and dyslexic subjects (lower curves). In control subjects the response amplitude ( $\pm$  SEM) to the non-degraded words (solid black lines) is stronger than the response to the symbol-strings (grey dotted lines) and most heavily degraded words (black dotted lines). (C) The mean ( $\pm$  SEM) peak strength of all sources related to letter-string analysis.

(Mann-Whitney *U*-test, non-significant); one control subject had as many as five sources of this kind. Activation was mainly distributed along the ventral visual stream, bordering on V1 area and extending laterally as far as V4v. Figure 2B displays the average time behaviour of all these visual sources to easily detectable (noise 0) and the most degraded words (noise 24) and to symbol-strings. Activation peaked around 100 ms after stimulus presentation and the source strength increased with increase of noise level, i.e. with local luminance contrasts.

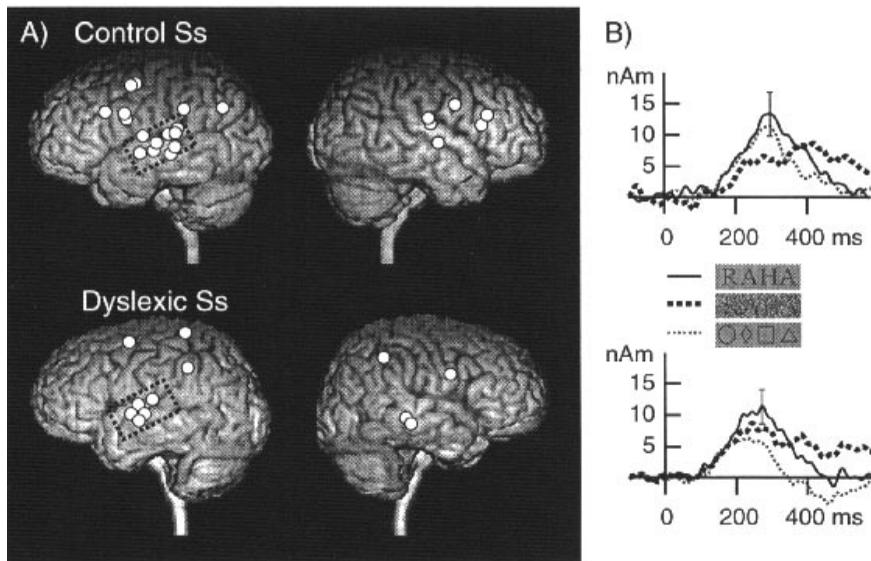
Statistical analysis of the time behaviour and strength of the activation related to visual feature processing was conducted on the peak amplitudes and latencies measured in individual subjects using mixed-model univariate analysis of variance with stimulus type (words on noise levels 0, 8, 16 and 24 and symbol-strings) as within-subjects factor and subject group (control and dyslexic subjects) as between-subjects factor. The main effect of subject group on latency of the responses across all stimulus types did not reach statistical significance when the analysis was performed including only the sources that peaked first in each subject ( $92 \pm 4$  ms in control subjects and  $101 \pm 6$  ms in dyslexic subjects for non-degraded words). Neither was a significant group difference discovered when the mean latencies of visual feature analysis sources in each subject were compared ( $116 \pm 3$  ms in control subjects and  $121 \pm 5$  ms in dyslexic subjects for non-degraded words). Even when the power of the statistical analysis was raised to the maximum level by treating each source as an independent observation, no statistically significant difference between groups emerged.

The main effect of subject group on response strengths across all stimulus types also failed to reach statistical significance regardless of whether the analysis was done across the sources that peaked first in each subject ( $8.3 \pm 2.1$  nAm for control and  $7.5 \pm 1.1$  nAm for dyslexic subjects in response to non-degraded

words) or across the mean source strengths in each subject ( $8.6 \pm 1.0$  nAm for control and  $6.8 \pm 1.0$  nAm for dyslexic subjects in response to non-degraded words). Even when all the sources were treated as independent observations, a significant between groups difference failed to emerge (see the histograms of Fig. 2C). It should further be noted that the mean response strengths of the control group were slightly biased by the data of two subjects, who showed more than two standard deviations stronger responses for all stimuli than the rest of the control group; exclusion of these two subjects would have reduced the mean source strength for non-degraded words from 8.4 to 7.0 nAm in Figure 2C. Noise increased the response strengths both in control [ $F(3,60) = 18.3, P < 0.0001$ ] and dyslexic subjects [ $F(3,27) = 3.8, P < 0.04$ ], as revealed by repeated-measures univariate analysis of variance performed across all visual feature analysis sources (within-subjects factor word type; words in noise levels 0, 8, 16 and 24). Thus, we were not able to detect any systematic differences in the amount, latency or strength of cortical sources related to visual feature analysis between fluent and dyslexic readers.

#### Activation Associated with Letter-string Processing

Figure 3A shows all the activated brain areas specifically associated with letter-string processing up to 180 ms after word presentation. In control subjects the activation was clearly left lateralized, concentrating in the left inferior occipito-temporal area. Ten of the 12 subjects showed activation in this area, modulated by the visibility of the word (Tarkiainen *et al.*, 1999). One control subject had a letter-string-specific source exclusively in the right occipital cortex and one control did not have any source that would have shown reliable modulation according to visibility or word-likeness of the stimuli. In sharp contrast with fluent adult readers, only two dyslexic subjects had letter-



**Figure 4.** (A) Sources preferentially activated by letter-string stimuli in the anterior brain regions in control (upper row) and dyslexic subjects (lower row). In both groups the highest number of sources was discovered in the left superior temporal lobe (dashed rectangles). (B) Time behaviour of all left temporal sources that were preferentially activated by letter-string stimuli in control (upper curves) and dyslexic subjects (lower curves).

string-specific activation in this area (dashed rectangle) (Fisher's exact probability test,  $P < 0.008$ ). Two dyslexic subjects also had activation more medially in the left occipital area, but more than two standard deviations posterior to the mean source location of the control subjects. Further, one dyslexic subject had two letter-string-specific sources in the right occipital area.

Figure 3B displays the averaged time behaviour of all letter-string-specific sources across control (upper curves) and dyslexic subjects (lower curves). The control subjects showed statistically significantly stronger and earlier activation to non-degraded words than either to symbol-strings or the most strongly degraded words around 150 ms after stimulus onset (Tarkiainen *et al.*, 1999). In dyslexic subjects, repeated-measures analysis of variance (within-subjects factor stimulus type; words on noise levels 0, 8, 16 and 24 and symbol-strings) revealed a significant main effect of stimulus type on the peak latency of the letter-string-specific sources [ $F(4,20) = 9.0$ ,  $P < 0.008$ ]. For activation strengths, the main effect of stimulus type only approached significance.

The strength of the letter-string-specific sources could not be compared between subject groups using the mean source strengths of each individual as observations due to the small number of sources detected in dyslexic subjects. When all sources were treated as independent observations, the overall strength of the letter-string specific activation was significantly weaker in dyslexic than in control subjects [repeated-measures analysis of variance with stimulus type as within-subjects factor and subject group as between-subjects factor;  $F(1,19) = 5.4$ ,  $P < 0.03$ ] (see Fig. 3C). Planned comparisons revealed that this difference was statistically significant for non-degraded ( $P < 0.009$ ) and moderately degraded words (noise levels 8 and 16,  $P < 0.02$ ). Thus, the earliest cortical activation related specifically to letter-string processing was abnormal in dyslexic subjects.

#### Late Letter-string-specific Responses in the Anterior Brain Regions

Degradation also affected the processing stages involved in reading beyond orthographic (letter) analysis. Figure 4A displays

all sources that were statistically significantly earlier or stronger to non-degraded words than to the most heavily degraded words and symbol-strings in the anterior brain regions. In both control and dyslexic subjects these letter-string-specific sources were extremely variable both in time behaviour and location. Most consistently, letter-string-specific sources were found in the left superior temporal cortex, where nine sources were detected in 8/12 control subjects (Tarkiainen *et al.*, 1999). Similarly, in the dyslexic subjects the highest absolute number of sources was detected in the left superior temporal region (five sources in five dyslexic subjects). In half of the dyslexic subjects temporal letter-string-specific sources were, however, missing.

The time behaviour of the temporal letter-string-specific sources is depicted in Figure 4B. In both control and dyslexic subjects the activation peaked around 300 ms but the beginning of activation seemed to be slightly different in the two groups. In all but one control subject the activation in the temporal area began around 200 ms, after culmination of the occipito-temporal letter-string-specific activation. However, in four out of five dyslexic subjects the activation in the left temporal area started already around 130 ms. None of these dyslexic subjects had a letter-string-specific activation in the left occipito-temporal area. Thus, dyslexic subjects appear to have a deviant pattern of cortical activation also in the left temporal cortex, possibly related to abnormal activation of the occipito-temporal area.

#### Discussion

We took advantage of the good temporal resolution of MEG to detect when in time the functional organization of single-word reading starts to dissociate between fluent and developmentally dyslexic adult readers. We used stimuli that differentiate between the early visual responses related to feature analysis and those specifically related to letter-string processing in fluent readers (Tarkiainen *et al.*, 1999). Our results showed that visual feature analysis in the postero-medial occipital areas around 100 ms after stimulus presentation was both spatially and temporally similar between control and dyslexic readers. However, activation reflecting letter-string analysis, peaking around 150 ms after

word onset in the left inferior occipito-temporal area in fluent readers, was undetectable in most of the dyslexic readers.

### ***Dissociating Between Object-specific and Non-specific Visual Processing***

Haemodynamic and intracranial studies of object and face processing have used object degradation to detect functional specialization within the ventral stream. Malach *et al.* (Malach *et al.*, 1995) decreased the detectability of objects and faces by adding visual noise to pictures. This manipulation, which was similar to the one used in the present study, decreased the strength of activation in the lateral occipital area. The opposite behaviour was observed in the V1 area where the activation increased with increasing noise level. Scrambled objects or texture patterns also produce more activation than non-scrambled objects or faces in the visual areas V1, V2 and V3 (Puce *et al.*, 1996; Grill-Spector *et al.*, 1998). Using intracranial recordings in epileptic patients, Allison *et al.* (Allison *et al.*, 1994) reported a stronger response around 120 ms to scrambled faces than to clearly identifiable faces in an electrode placed on the surface of the occipital pole. Both noise and scrambling increase the number of local luminance-contrast borders, i.e. the amount of visual features. Puce *et al.* (Puce *et al.*, 1996) have suggested that the activation along the ventral stream in areas V2, VP and V4 is to be considered an intermediate step between object processing in the primary visual and object-specific visual areas.

The study of Tarkiainen *et al.* (Tarkiainen *et al.*, 1999) is in accordance with previous imaging studies with respect to location and timing of visual feature analysis. In the present study, we could detect no differences between fluent and dyslexic readers at this non-specific level of visual object analysis. It should be noted, however, that our approach provided only a crude overall view to visual cortical activation related to feature analysis. As knowledge of human visual areas is rapidly increasing, more detailed mapping of the functional properties of visual areas in dyslexia is clearly warranted in the future.

### ***Processes Affected by the Visibility of the Word***

As reported by Tarkiainen *et al.* (Tarkiainen *et al.*, 1999), the visibility and word-likeness of the stimulus affected activation in the left inferior occipito-temporal cortex in fluent adult readers – activation in this area was earlier or stronger for both syllables and words than for symbol-strings. Thus, this activation likely reflects pre-lexical, orthographic analysis. The letter-string-specific responses in the left occipito-temporal area of the fluent readers are in line with previous imaging studies with respect to location (Puce *et al.*, 1996) and timing (Nobre *et al.*, 1994). In the dyslexic group, only two individuals showed letter-string-specific activation in the left inferior occipito-temporal cortex. This finding agrees with earlier MEG (Salmelin *et al.*, 1996; Helenius *et al.*, 1999) and haemodynamic (Rumsey *et al.*, 1997; Shaywitz *et al.*, 1998) studies of dyslexic adults showing delayed and/or reduced activation of occipito-temporal areas during reading. Thus, in contrast to the essentially identical activation with respect to visual feature analysis in dyslexic and fluent readers, the earliest cortical activation related specifically to letter-string processing was abnormal in dyslexic subjects. Lesion compromising left inferior occipital areas leads to selective impairment of reading in the absence of obvious difficulties with spoken language, i.e. pure alexia (Damasio and Damasio, 1983; Henderson, 1986). When patients with pure alexia retain residual word recognition skills, reading proceeds laboriously in

letter-by-letter fashion. Thus, studies on both acquired and developmental dyslexics suggests an important role for the left occipito-temporal area in fluent automated reading.

The naming speed of written words decreases when words are visually degraded (Meyer *et al.*, 1975; Tarkiainen *et al.*, 1999). Thus, not only is orthographic processing affected, but all processes beyond this stage that are involved in the production of oral output. Effectively, stimulus degradation can help to reveal activation directly linked to word recognition, although the exact nature of activation beyond the pre-lexical stage cannot be determined using the present stimuli. Both fluent and dyslexic readers showed activation in the left superior temporal area that was influenced by the visibility of the words. In control subjects, the temporal activation could reflect semantic processing (Helenius *et al.*, 1998). In dyslexic subjects, however, the degradation-dependent activation was either undetectable (five subjects) or abnormally early (four subjects). The reduced activation of temporal areas is in accordance with two previous MEG (Salmelin *et al.*, 1996; Helenius *et al.*, 1998) and haemodynamic (Rumsey *et al.*, 1997; Shaywitz *et al.*, 1998) studies. The abnormally early activation latency is not readily interpretable based on the previous studies. However, as the early temporal activation was associated with undetectable letter-string-specific occipito-temporal signals, temporal activation might have a compensatory role in dyslexic readers. Further, it is worth noting that, unlike fluent readers, who seem to have essentially the same pattern of cortical activation across different reading related MEG studies (single words, sentences), in dyslexic readers the pattern of activation can vary substantially across studies (Salmelin *et al.*, 1996; Helenius *et al.*, 1999). This could indicate unstable and unautomated processing of written words in dyslexic readers, who may be utilizing a multitude of individual and task-dependent strategies in order to aid visual word recognition.

### ***Causes of the Defective Pre-lexical Word Analysis in the Dyslexic Brain***

In the evolution of human species reading has appeared relatively recently and, thus, cortical areas specialized in processing written language are likely to emerge through environmental exposure. Consequently, any processing deficit that hampers the acquisition of fluent reading could result in abnormal reading-related visual activation. For example, poor phonological awareness could prevent the association between sounds and corresponding visual entities both at the behavioural level (Frith, 1985) and in the brain (Salmelin *et al.*, 1996; Helenius *et al.*, 1999) and, thus, impede the functional maturation of a word/letter-string-specific visual area. But visual problems cannot be excluded either. The ventral visual stream is crucial for object and word recognition, and it is reciprocally connected with the dorsal stream involved in processing spatial information and motion (Ungerleider and Mishkin, 1982; Felleman and Van Essen, 1991; Ungerleider, 1995). Magnocellular visual functioning, dominating in parts of the dorsal stream (Maunsell *et al.*, 1990), has been suggested to have an important role in reading, especially for encoding letter positions within words (Cornelissen *et al.*, 1998). Accordingly, deficient magnocellular functioning in dyslexic individuals (Lovegrove *et al.*, 1986; Livingstone *et al.*, 1991; Cornelissen *et al.*, 1995; Stein and Walsh, 1997; Demb *et al.*, 1998) could be manifested as impaired letter position encoding during reading. This again could impede tuning of letter-string-specific neuronal populations. Similarly, a deficit in attention-related functions [for review, see Stein and

Walsh (Stein and Walsh, 1997)] or poor integration of visual and phonological codes could be reflected in functional tuning of letter-string-specific areas. Unlike the causal relation between phonological problems and dyslexia (Bradley and Bryant, 1983), the contribution of other factors to poor reading is, however, still mostly hypothetical. In the future, it would be of great importance to be able to accurately characterize cortical dynamics of reading acquisition, and its dependence on phonological or visual processing in individual brains, in order to clarify the mystery of poor reading in developmental dyslexia.

## Notes

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