

Explicit and implicit processing of words and pseudowords by adult developmental dyslexics

A search for Wernicke's Wortschatz?

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Summary

Two groups of male university students who had been diagnosed as dyslexic when younger, and two groups of control subjects of similar age and IQ to the dyslexics, were scanned whilst reading aloud and during a task where reading was implicit. The dyslexics performed less well than their peers on a range of literacy tasks and were strikingly impaired on phonological tasks. In the reading aloud experiment, simple words and pseudowords were presented at a slow pace so that reading accuracy was equal for dyslexics and controls. Relative to rest, both normal and dyslexic groups activated the same peri- and extra-sylvian regions of the left hemisphere that are known to be involved in reading. However, the dyslexic readers showed less activation than controls in the left posterior inferior temporal cortex [Brodmann area (BA) 37, or Wernicke's Wortschatz], left cerebellum, left thalamus and medial extrastriate cortex. In the implicit reading experiment, word and pseudoword processing

was contrasted to visually matched false fonts while subjects performed a feature detection paradigm. The dyslexic readers showed reduced activation in BA 37 relative to normals suggesting that this group difference, seen in both experiments, resides in highly automated aspects of the reading process. Since BA 37 has been implicated previously in modality-independent naming, the reduced activation may indicate a specific impairment in lexical retrieval. Interestingly, during the reading aloud experiment only, there was increased activation for the dyslexics relative to the controls in a pre-motor region of Broca's area (BA 6/44). We attribute this result to the enforced use of an effortful compensatory strategy involving sublexical assembly of articulatory routines. The results confirm previous findings that dyslexic readers process written stimuli atypically, based on abnormal functioning of the left hemisphere reading system. More specifically, we localize this deficit to the neural system underlying lexical retrieval.

Keywords: dyslexia; phonological deficit; explicit reading; implicit reading; word sound

Abbreviations: BA = Brodmann area; NART = National Adult Reading Test; rCBF = regional cerebral blood flow; SPM = statistical parametric mapping; WRAT = Wide Range Achievement Test—Revised; WAIS-R = Wechsler Adult Intelligence Scale—Revised

Introduction

Developmental dyslexia is a neurocognitive disorder with a strong genetic component (see review by DeFries *et al.*, 1997), and should not be confused with poor reading achievement which can occur for a variety of different reasons (Rutter and Yule, 1975). Definitions of dyslexia suffer greatly from problems inherent in behavioural observations, which change with age and general ability (Frith, 1997). The attempt to make definitions dependent on arbitrarily defined

discrepancies between reading skill and general skills has proved unsatisfactory (Siegel, 1992; Lyon, 1995). While the hallmark of dyslexia is the pronounced difficulty in the acquisition of literacy, many dyslexics eventually achieve satisfactory scores on standard reading tests. Likewise, dyslexic readers in different languages experience quite different problems in reading and writing, since the orthography of a specific language has a profound impact on

the manifestation of dyslexia in reading tests (Landerl *et al.*, 1996). Subtle cognitive impairments in language processing outside reading and writing are apparent before school age (Scarborough, 1990), as well as in adulthood (e.g. Bruck, 1992; Elbro *et al.*, 1994; Snowling *et al.*, 1997). Behavioural criteria are therefore an inadequate basis for a unified definition of dyslexia. It is also necessary to identify the nature of the putative cognitive impairments and to investigate the physiological anomalies in the underlying neural systems.

Clinical signs of dyslexia that appear to be independent of age and ability include impairments in speech processing, in particular on tasks requiring manipulation and memory of segmental speech sounds (see Snowling and Nation, 1997). Similarities to specific language impairments indicate left hemisphere abnormalities. Difficulties in auditory temporal processing and temporal order judgement (Tallal, 1980; Tallal *et al.*, 1993) and specific deficits in neuromotor tests (Kinsbourne *et al.*, 1991) also point to left hemisphere impairments. Other signs of dyslexia concern low-level difficulties in the visual processing of fast moving stimuli (see Lovegrove, 1993). These difficulties implicate the magnocellular system bilaterally (Livingstone *et al.*, 1991). Unstable binocular control has also been found to relate to reading difficulties (Cornelissen *et al.*, 1992), and Slaghuys and colleagues suggested that visual and language processing deficits co-occur in dyslexia (Slaghuys *et al.*, 1993).

A number of brain imaging studies have targeted some of the underlying processes that are assumed to be compromised in dyslexia, and have attempted to locate brain regions with abnormal activation in dyslexics. Flowers and colleagues were the first to test the hypothesis of abnormal left hemisphere activation in dyslexics during a language task (Flowers *et al.*, 1991). They found that degree of reading impairment correlated with reduced activation in posterior temporoparietal cortex during an auditory rhyming task. Rumsey and colleagues (Rumsey *et al.*, 1992), Paulesu and colleagues (Paulesu *et al.*, 1996) and Shaywitz and colleagues (Shaywitz *et al.*, 1998) also scanned dyslexics during rhyme judgements. The studies all show abnormal activation patterns in the left perisylvian and extrasylvian temporal cortices. Eden and colleagues targeted magnocellular system weakness, and scanned volunteers while they watched moving dot patterns (Eden *et al.*, 1996). Demb and colleagues found a correlation between brain activation of components of this system and degree of reading difficulty in adult dyslexics (Demb *et al.*, 1998). Lehmkuhle and colleagues showed abnormal evoked responses to low-spatial frequency targets in dyslexic children (Lehmkuhle *et al.*, 1993). In all these studies dyslexics were found to differ at the physiological level even when task demands were simple. This strongly confirms the notion of dyslexia as a neurocognitive developmental disorder that must be distinguished from the variety of reading problems found in school-age populations.

The phonological processing hypothesis of dyslexia rests on robust behavioural evidence and claims to provide a direct link between the putative cognitive deficit and the specific

problems of dyslexics in the acquisition of literacy (see review by Snowling, 1991). Literacy acquisition, especially in alphabetic writing systems, critically involves segmentation of speech into phonemes (Brady and Shankweiler, 1991). Impairment in this process leads to reading failure (Bryant and Bradley, 1978). Phonemes have to be related to graphemes, and grapheme–phoneme conversions have to be related to whole word sound. This involves both piecemeal or assembled phonology, and whole-word or addressed phonology (see Morton, 1980). In English, the mapping between these two processes is complex, because whole word sound cannot be reliably derived from piecemeal assembled sounds. The phonological deficit hypothesis of dyslexia proposes that all of these steps are problematic for dyslexics and cause reading skills to develop atypically. The phonological deficit hypothesis is amenable to be studied at the physiological level, since the neurological substrate of normal phonological processing has been investigated in a number of neuro-imaging studies. These studies have converged, reliably demonstrating that structures in the perisylvian and extrasylvian regions of the dominant language hemisphere are dedicated to phonological processes (Démonet *et al.*, 1994). Tasks relying on segmented and assembled phonology elicit activations in the supramarginal gyrus/superior temporal gyrus (BA 40/22: Paulesu *et al.*, 1993; Price *et al.*, 1997b) and premotor cortex/Broca's area (BA 6/44: Paulesu *et al.*, 1993; Démonet *et al.*, 1994). In contrast, tasks that involve addressed phonology, picture, colour or letter-naming, for example, activate the left frontal operculum and the left posterior inferior temporal cortex (BA 37: Bookheimer *et al.*, 1995; Price and Friston, 1997).

Abnormalities of activation in perisylvian and extrasylvian regions of the left hemisphere have been associated with impaired phonological processing in developmental dyslexia (Rumsey *et al.*, 1992; Paulesu *et al.*, 1996; Shaywitz *et al.*, 1998). However, functional imaging methods for studying directly the processes involved in word recognition in dyslexic readers have not been used until recently. Salmelin and colleagues measured electrical activity (MEG) of the brains of Finnish-speaking developmental dyslexics and control readers while they silently read words (concrete and abstract) and pseudowords (Salmelin *et al.*, 1996). In contrast to control readers, dyslexics failed to activate the left inferior temporo-occipital region during the first 200 ms of viewing the words. Even between 400–700 ms post-stimulus onset, the dyslexics' activation of the left temporal lobe was significantly less than that of the controls; however, the dyslexics activated the left inferior frontal lobe within this time window while the controls did not. Pseudowords elicited greater activation than words in the majority of the controls (in the left middle temporal lobe and central sulcus) and in half of the dyslexics (in the temporoparieto-occipital region). However, as no measure of reading accuracy was taken and participants gave no overt response to the stimuli, it is possible that some performance differences existed in the dyslexics' reading of the words and pseudowords compared

with controls. It cannot be ruled out that the dyslexics' failure to activate the temporal language areas reflects a failure to decode the stimuli with sufficient accuracy to activate the semantic and naming areas of the brain.

Rumsey and colleagues also studied reading words and pseudowords in dyslexics, using PET scanning (Rumsey *et al.*, 1997). They presented adult developmental dyslexics and chronological age-matched readers with a self-paced task where they had to read irregular, low frequency words and pseudowords that were not analogous to familiar words (e.g. phalhap). Significantly different levels of activation were observed between the two groups of readers. Relative to the control readers the dyslexics demonstrated reduced activation of mid to posterior temporoparietal cortex, in particular the left superior and middle temporal gyri, in the left fusiform and the right peri-rolandic region. As the task used to elicit these activations was self-paced, however, dyslexics and controls saw a different number of stimuli. The authors themselves point out that this difference may have contributed to the observed between-group differences in activation. These two studies are consistent with previous findings of abnormal activations in dyslexia in the left temporoparietal regions of the brain during language processing tasks (Flowers *et al.*, 1991; Hagman *et al.*, 1992; Rumsey *et al.*, 1992; Galaburda *et al.*, 1994). The present studies aimed to explore and extend these findings taking into account the methodological concerns raised above. In addition they attempted to separate abnormal activations associated with compensation during accurate decoding, and those associated with automatic processing of print, by studying explicit (Study 1) and implicit (Study 2) reading.

In Study 1 we scanned compensated adult dyslexics while they read words and word-like pseudowords aloud. We presented one stimulus every 3 s, thus equating the rate of stimulus presentation for the two groups, and at the same time providing a sufficiently slow pace to allow accurate decoding by all individuals. Furthermore, we presented phonologically and orthographically simple stimuli, and produced very word-like pseudowords by only changing the internal consonants of the words (cassot for carrot). This was done to allow high reading accuracy in the dyslexic readers and thus to ensure that any differences in brain activation between dyslexics and controls would not merely reflect differences in performance levels. In line with the previous studies, we expected that the posterior temporal parietal regions of the left hemisphere would be less highly activated by dyslexic readers.

Study 1: explicit reading of words and pseudowords

Participants

We tested six adult right-handed males with developmental dyslexia and six male controls who had no history of reading impairment. All participants were university students with

English as a first language, all were physically healthy and none reported a history of neurological or psychiatric disorder. The mean age of the dyslexic group was 23 years (± 5.2), and the mean age of the control group was 23.2 years (± 2.9). Informed written consent was obtained from all participants before testing began. The dyslexic readers all had a documented history of reading difficulty that had been identified in childhood, and all had received special tuition in literacy skills as a consequence. In spite of these chronic literacy problems, all were well-compensated readers as demonstrated by their entrance into university. Control readers without any history of reading problems were recruited from the same universities.

Methods

Psychometric tests

Participants received a battery of standardized tests and experimental measures designed to assess literacy and literacy related skills. Verbal, performance and full-scale IQ were determined using short forms of the Wechsler Adult Intelligence Scale—Revised (WAIS-R). Reading and spelling ability were tested using the National Adult Reading Test (NART; Nelson, 1983) and the Wide Range Achievement Test—Revised (WRAT-R; Jastak and Wilkinson, 1984).

Word recognition tests

Specially constructed lists of words and pseudowords were presented on a laptop computer, and naming latency and accuracy were recorded via a voice-key to assess word recognition and grapheme–phoneme decoding ability. The stimuli consisted of two- and three-syllable words, avoiding irregular spelling patterns. Pseudowords were created from the words by maintaining the 'word envelope' whilst changing internal consonants. The word 'satin', for example, became 'samin'; and lemon became 'lexon'. More examples are provided in Appendix 1. Participants were asked to name the word as soon as they had recognized it. As soon as a verbal response had been detected, the stimulus disappeared. As a base line measure of response latency, we also used a dot stimulus.

Experimental tests

Participants also received a range of tasks thought to tap aspects of phonological processing. These included a Spoonerism task (to assess phonological segmentation and manipulation ability; after Perin, 1983), a measure of phonemic fluency (to assess efficiency of phonemic lexical access), a test of accuracy of immediate recall of either short or long words (to assess auditory verbal short-term memory for words; after Baddeley *et al.*, 1975), the WAIS digit span test (a measure of verbal short-term memory for digits), and

a digit-naming task (to measure naming speed; after Spring and Davis, 1988). See Appendix 1 for details.

Activation tasks

The scanning period involved three experimental conditions: two activation conditions (reading aloud words and pseudowords) and a passive (eyes closed) rest condition. Eyes closed was selected as a baseline condition against which to compare the activations associated with reading words and pseudowords. The rest condition has been commonly used in our laboratory, so it will be possible to interpret the present data in terms of previous neuroimaging and neurophysiological findings that have attempted to localize the functional components involved in reading. The three experimental conditions were presented in a fixed counter-balanced design (ABCCBAABCCBA); each condition was presented four times. This study followed a factorial design with reading ability (dyslexic versus non-dyslexic) as the between-group factor and with task (reading words, reading pseudowords and rest) as the within-group factor.

The activation conditions required the reading of either familiar words (bi-syllabic, regular, concrete nouns, e.g. valley, body, carrot) or unfamiliar but word-like pseudowords, e.g. vassey, bofy, cappot). As in the pre-test of word-recognition ability, the pseudowords were created from the words by changing the internal consonants. Stimuli used during scanning had not been presented during the pre-test. The administration differed also from the pre-test in that each stimulus was presented for 1 s and the inter-stimulus interval was 2 s. Presentation of stimuli was via the SuperLab program (version 1.68: Cedrus Corporation) run on an Apple Power Macintosh computer. Stimuli were presented in lower-case Times, 48 point font size (black letters on a white background) at the rate of one every 3 s. A block of 22 words or pseudowords was presented per scan in the centre of a computer monitor; this monitor was suspended above the scanning bed at a comfortable distance from the subject, orthogonal to their line of vision. Participants' verbal responses (reading of words and pseudowords) were recorded.

PET scanning procedure

Regional cerebral blood flow (rCBF) was measured using a CTI Siemens Ecat HR + PET scanner (CTI Inc., Knoxville, Tenn., USA). Data were acquired with inter-detector collimating septa retracted (Townsend *et al.*, 1991). Twelve consecutive scans were obtained for each subject following a transmission scan, implemented with an exposed $^{68}\text{Ge}/^{68}\text{Ga}$ source, to correct for attenuation. Each activation scan involved the intravenous administration of 5 mSv of H_2^{15}O at the constant rate of 10 ml/min. From the start of each scan background radiation was measured for 30 s, after which the infusion was given. The activation task was started ~30 s later, 10 s prior to the onset of the acquisition period.

Acquisition lasted for 90 s. After correcting for background activity, the true counts accumulated during this period were taken as an index of cerebral blood flow (Fox and Mintun, 1989). This protocol conforms with guidelines established by ARSAC UK and was approved by the Medical Ethics Committee of the Institute of Neurology.

Data analysis

Head movements which occurred during the course of the PET scan were corrected by realigning the time series with the first scan. The reconstructed transaxial PET images were spatially normalized for brain size and shape (Friston *et al.*, 1995a) so that the spatially normalized images consisted of $2 \times 2 \times 4$ mm voxels. These images were subsequently smoothed in three directions with a Gaussian filter (full-width at half-maximal) of $16 \times 16 \times 16$ mm. This smoothing had the effect of increasing signal-to-noise ratio and allowing for normal between-subject variation in gyral anatomy. Task-related differences in rCBF were examined using statistical parametric mapping (SPM96) software (Friston *et al.*, 1995b) on a SPARC1 workstation (Sun Microsystems Inc., Surrey, UK). Analyses were performed in MATLAB version 4.2c (MathsWorks Inc., Natick, Mass., USA). Data were analysed using subject-specific repeated measures ANCOVA with images scaled to a grand mean of 50. Statistical parametric maps of adjusted mean rCBF were produced for each condition/group along with adjusted error variance data for each. To protect against the reporting of false positive results, activations are only reported where they reach a significance level of $P < 0.001$ (Bailey *et al.*, 1991).

The linear contrast, identified significant activations for (i) words – rest, (ii) pseudowords – rest, (iii) words – pseudowords and (iv) pseudowords – words (in both the dyslexic group and the normal group), and the interactions between each of these contrasts and subject group. To distinguish increased activation for words from decreased activation for pseudowords (and vice versa), we only report differences between words and pseudowords when one or other or both conditions resulted in significant activation relative to rest at a threshold of $P < 0.01$ (see Table 6).

Results

Psychometric measures

As shown in Table 1, no significant between-group differences emerged in either full-scale IQ ($P = 0.3$), performance IQ ($P = 0.9$) or verbal IQ ($P = 0.09$). Analysis of the data from the standardized literacy tests revealed impaired performance of the dyslexics relative to the controls [NART ($F(1, 10) = 20.0$; $P = 0.001$); WRAT reading ($F(1, 10) = 5.1$; $P = 0.05$); WRAT spelling ($F(1, 10) = 10.4$; $P < 0.01$)]. The dyslexics were also less accurate on the timed word recognition tests [words: $F(1, 10) = 6.0$; $P = 0.04$; pseudowords: $F(1, 10) = 13.1$; $P < 0.01$]. They were also

Table 1 Subject characteristics: reading and phonological abilities

Variable	Dyslexics (n = 6)		Controls (n = 6)		P
	Mean	SD	Mean	SD	
Age (years)	23.0	5.2	23.2	2.9	n.s.
<i>IQ tests (WAIS-R)</i>					
Full-scale	107.7	10.2	112.8	5.8	n.s.
Verbal	106.0	7.9	114.0	7.2	n.s.
Performance	108.5	14.7	108.3	10.3	n.s.
<i>Standardized literacy tests</i>					
Reading NART (errors; maximum = 50)	28.3	8.5	12.0	2.6	***
Reading WRAT (standardized scores)	101.5	13.9	114.2	3.7	*
Spelling WRAT (standardized scores)	82.3	17.6	108.2	8.7	**
<i>Single word/pseudoword reading</i>					
Accuracy (maximum = 40):					
words	38.8	1.2	40.0	0	*
pseudowords	29.7	6.1	38.8	1.3	**
Latency† (ms):					
words	817.6	199.4	558.5	45.0	**
pseudowords	1429.0	251.1	727.0	56.2	***
<i>Phonological measures</i>					
Spoonerisms (errors; maximum = 12)	5.2	4.2	0.5	0.8	*
Spoonerisms (s/pair)	19.4	8.0	7.7	3.9	**
Phonemic fluency (words in 30 s)	18.0	5.1	24.2	7.3	n.s.
Digit naming: 50 digits (s)	20.2	3.7	12.2	1.1	**
Auditory STM (mean correct; maximum = 6)	2.2	0.91	4.0	0.90	**
WAIS digit span (maximum = 19)	7.7	1.9	11.2	1.5	**

n.s. = non-significant. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; †latency based on correct responses only.

slower with both types of stimuli [words: $F(1, 10) = 9.6$; $P = 0.01$; pseudowords: $F(1, 10) = 44.6$; $P < 0.001$], but did not differ in their response latencies to a dot stimulus.

The dyslexic readers were impaired on the Spoonerism task: they made more errors than the controls [$F(1, 10) = 7.2$; $P = 0.02$] and took over twice as long to complete the task [$F(1, 10) = 9.4$; $P = 0.01$]. They also took significantly longer than controls to complete the digit-naming task [$F(1, 10) = 25.4$; $P < 0.001$]. The difference in phonemic fluency was in the predicted direction, but not significant ($P = 0.1$). The dyslexic participants also demonstrated impairments in auditory short-term memory for word recall [$F(1, 10) = 11.9$; $P < 0.01$] and in digit span [$F(1, 10) = 13.0$; $P < 0.01$].

Behavioural measures during PET activation study

No significant difference in accuracy was found between the dyslexic and control participants on either the word reading ($P = 0.28$) or the pseudoword reading ($P = 0.06$) task performed during PET scanning (see Table 2).

Regions of activation common to dyslexics and controls

As shown in Table 3, an extensive set of regions was activated in common for the dyslexics and controls during the reading of words and pseudowords relative to rest. The activated

Table 2 Behavioural measures during PET scanning: stimuli read correctly

Stimuli	Dyslexics		Controls		P
	Mean	SD	Mean	SD	
Words (maximum = 88)	85.2	3.8	87.0	1.1	n.s.
Pseudowords (maximum = 88)	73.3	10.3	83.0	4.5	n.s.

n.s. = non-significant.

systems included the cerebellum/fusiform, precentral gyri, superior temporal gyri (BA 38), inferior parietal and frontal regions.

Areas of differential activity, irrespective of word type

The control readers activated several regions to a significantly greater degree than the dyslexics (see Fig. 1). These regions had left hemisphere foci in the posterior inferior temporal cortex (BA 37) and the caudate/thalamus, the cerebellum and the right lingual gyrus. In only one respect did the dyslexic participants show increased activation relative to controls. This was in BA 6/44, in the region of Broca's area and the adjacent premotor cortex of the left hemisphere (see Table 4).

Table 3 Common areas activated by dyslexics and controls

Foci of activation	Words – rest				Pseudowords – rest			
	x	y	z	Z score	x	y	z	Z score
Cerebellum	-20	-60	-18	6.4	-16	-58	-34	3.6
	2	-34	-40	n.s.	2	-38	-34	3.5
Bilateral fusiform/ medial extrastriate	-22	-94	-10	8.1	-22	-94	-10	8.8
	-28	-60	-20	7.0	-28	-60	-20	9.1
	-34	-72	-20	6.5	-32	-74	-10	6.5
	-40	-56	-26	6.0	-38	-60	-24	8.7
	28	-98	-8	7.5	34	-88	-8	7.1
Medial extrastriate	38	-62	-20	3.1	42	-64	-20	4.7
	-6	-74	4	3.7	-6	-78	10	6.7
	-10	-90	4	5.0	-8	-86	-10	4.7
Insula	12	-68	-20	6.8	8	-68	-18	7.8
	-30	4	8	3.0	-34	14	6	3.9
Thalamus	-16	-14	6	4.6	-18	-10	8	5.4
	-24	-6	16	3.3	-22	-4	12	4.2
Inferior parietal				n.s.	44	-58	56	3.3
Superior temporal gyri	-68	-42	12	3.4	-68	-42	12	5.5
	-70	-26	4	4.0	-70	-26	4	5.3
	-52	2	12	3.2	-52	4	14	4.2
	50	-24	8	3.9	56	-24	8	4.6
	64	-4	8	3.8	68	-4	0	4.8
	64	-36	12	5.6	62	-36	10	5.1
Bilateral precentral gyri	-52	-6	46	4.4	-48	-8	44	4.8
	-54	-4	30	4.9	-54	-4	30	5.6
	54	-8	44	6.9	54	-8	42	6.6
	66	-2	24	4.3	66	2	22	4.4
Frontotemporal	50	10	2	4.8	50	10	2	6.1
	62	22	-4	n.s.	60	26	-8	3.6
Ventromedial frontal (BA 11)	-26	26	-32	5.9	-26	26	-32	6.1
Inferior frontal gyrus (BA 47)	22	30	-28	4.6	22	30	-28	4.5

This table shows focal maxima and Z scores for activated brain regions. The *x*, *y* and *z* coordinates refer to the three orthogonal dimensions of Talairach and Tournoux's atlas (Talairach and Tournoux, 1988). The *x* coordinate indicates regions (millimetres) to the left (-) and right (+) of the anterior commissure; *y* indicates mm anterior (+) and posterior (-) to the commissure; *z* to regions superior (+) and inferior (-) to this reference point. The Z scores indicate the magnitude of rCBF change at each location, all significant at $P < 0.001$. n.s. = non-significant.

Discussion

The two groups of readers proved to be well matched in terms of age, educational attainment and intelligence. While possessing reading skills that are average in terms of general population norms, the dyslexics were still significantly impaired relative to their peers on literacy tasks. They were also impaired on tasks tapping phonological ability in auditory presentation. This confirms previous studies indicating a persistent phonological deficit in developmental dyslexia even in highly able and compensated adults. The nature of this deficit can be explored through the functional imaging results.

The functional imaging results replicated some of the findings reported by Salmelin and colleagues (Salmelin *et al.*, 1996) and Rumsey and colleagues (Rumsey *et al.*, 1997). As in these previous studies, similar brain systems were activated for words and pseudowords. This suggests that similar strategies were used for reading words and pseudowords. Both normally skilled and dyslexic readers showed activations in the classical language regions and in regions associated

with the sensory aspects of reading: visual activations in the occipital lobe, receptive auditory processing in the superior temporal lobe and articulation in precentral cortices (Price *et al.*, 1994, 1996a; Bookheimer *et al.*, 1995; Rumsey *et al.*, 1997). However, there were also significant group differences. While both samples relied on a common distributed language system for word recognition, dyslexics showed an anomalous activation pattern as regards its various components. Again, as in the two previous studies, they showed less activation in the posterior parts, but more in the anterior parts. Our experimental design was successful in ensuring that the two groups did not differ in decoding accuracy during PET scanning. Thus, unlike the previous studies, differences in activation are less likely to be due to quantitative differences in performance level, but can be safely attributed to qualitative differences in reading processes.

The areas where dyslexics showed reduced activation relative to normals were the left posterior inferior temporal cortex, the left and midline cerebellum, the left thalamus and

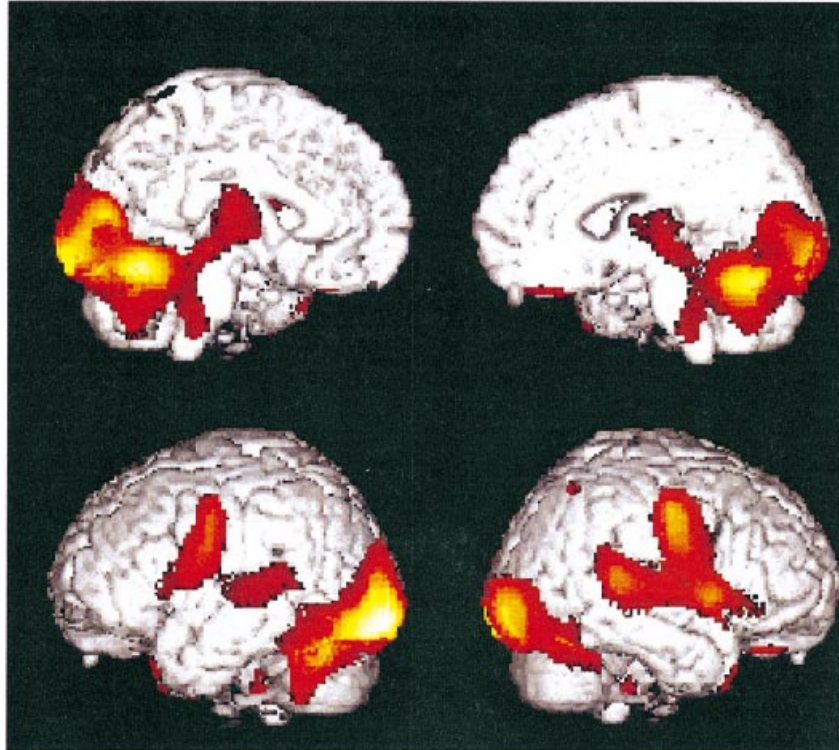


Fig. 1 Networks of rCBF activation common to the dyslexics and controls reading aloud words and pseudowords. Activated systems include the bilateral cerebellum/fusiform, precentral gyri, superior temporal gyri, inferior parietal and frontal regions. Significant voxels are rendered onto lateral and medial surfaces of idealized brains corresponding to the stereotactic space defined by Talairach and Tournoux (1988). As in Fig. 2, areas of significant activation are shown in colour.

Table 4 Differences in brain areas activated, between dyslexics and controls, irrespective of word type

Foci of activation	Controls > Dyslexics				Dyslexics > Controls			
	x	y	z	Z score	x	y	z	Z score
Medial extrastriate/ lingual gyrus	-2	-80	0	3.03				
	6	-80	-18	4.06				
	16	-100	-8	3.93				
	12	-104	0	3.67				
Cerebellum	-28	-86	-26	3.80				
	-16	-54	-28	3.02				
	-10	-58	-42	3.38				
Basal temporal (BA 37)	2	-30	-48	3.00				
	-50	-48	-12	3.64				
	-54	-68	-14	3.58				
	-48	-56	-6	3.13				
Caudate/thalamus	-14	-20	0	3.15				
	-16	-22	18	3.03				
	-18	-26	6	2.79				
Premotor (BA 6/44)					-64	0	26	3.09

Stereotactic conventions as described in Table 3. Z scores significant at $P < 0.001$.

the medial extrastriate cortex. All but the medial extrastriate cortex have previously been found to be activated for reading, picture naming, letter naming and colour naming (Price and Friston, 1997), suggesting that they encompass part of a modality-independent lexical retrieval system. The medial extrastriate region is activated for reading aloud relative to

reading silently (Price *et al.*, 1997a). It is an area that Petersen and colleagues attributed to the word-form system (Petersen *et al.*, 1990), but this conclusion has been questioned by the finding that it also responds to non-orthographic stimuli (Indefrey *et al.*, 1997). One possible hypothesis is that reading aloud relative to reading silently normally alters the way that

subjects attend to the visual features in the word (Price *et al.*, 1997). For instance, activation in the medial extrastriate cortex is enhanced when subjects attend to the global structure of a visual stimulus (Fink *et al.*, 1996). The hypothesis that the dyslexics are focussing less on the global properties of the word is consistent with evidence that they were more reliant on sublexical processing. This evidence was indicated by the finding that dyslexics showed increased activation in an area of the premotor cortex (BA 44/6) that has been associated with articulatory coding (Démonet *et al.*, 1992). Hagoort and colleagues have argued recently that assembling articulatory programmes from sublexical segments greatly increases the computational load on articulation relative to familiar articulatory routines (Hagoort *et al.*, 1999). The increased activation for the dyslexics in a region associated with articulation is therefore consistent with increased demands on sublexical processing. If our hypothesis is correct—that dyslexics are increasing the demands on articulatory processes to compensate for reduced efficiency in lexical retrieval—then a clear prediction arises: dyslexics should not show an increase in activation of Broca's area when reading aloud is not required. Our second study tests this prediction. In addition, the second study uses false font stimuli as the control rather than rest, which should reduce differences in visual processing between reading and control conditions.

Study 2: implicit reading of words and pseudowords

In normal skilled readers, the presence of words or pseudowords in the visual field automatically activates semantic and phonological processes even when the intention is not to read (Van Orden *et al.*, 1988; Macleod, 1991). Price and colleagues, for example, undertook a functional imaging study to investigate the cerebral correlates of implicit reading in normal readers (Price *et al.*, 1996a). In this study participants were asked to perform a visual feature detection task, making a non-linguistic judgement about the physical form of word, pseudoword, consonant letter string and false font stimuli. The experimental paradigm used in Study 2 is closely modelled on that of Price and colleagues in that participants were required to carry out a graphic feature detection task with words, pseudowords and false font strings (Price *et al.*, 1996b); and in none of the conditions were participants required to read the stimuli. It is conceivable that, in the absence of explicit instructions to read, no activation of the language areas would be found in the brains of dyslexic readers. However, we expected that compensated dyslexics would have acquired a sufficiently high level of automatic word-recognition skills to make this outcome unlikely. Thus we expected to find the same decreased activation in the posterior parts of the language system which has been consistently shown in all activation studies to date. If the increase in activity found in the previous study in

anterior parts of the language system was due to effortful processing in explicit reading, then implicit reading should not be associated with such an increase.

Participants

The same selection criteria were used as in the previous study. Six dyslexic and six control readers were recruited from the same universities and were again matched for age, educational level and IQ. The mean age of the dyslexic group was 24.5 years (± 6.1), whereas the mean age of the control group was 24.5 years (± 2.9). Participants were tested with the same psychometric test battery as in Study 1, and gave informed consent before testing began.

Methods

Activation tasks

During each PET scan participants performed a feature detection task. This involved detecting the presence or absence of ascenders (graphic features which go above the midline of the word, e.g. b, l, t) within visually presented words, pseudowords and false font strings. The words and pseudowords were a subset of those employed in Study 1; the false fonts were created by substituting letters in the real words with non-letters matched for size and presence or absence of ascenders. Participants were familiarized with the task requirements prior to scanning and a short practice session was provided for each type of stimulus. It was emphasized that this was not a reading task but a feature detection task, and participants were told not to bother reading the stimuli. If participants experienced uncertainty with either the task demands or with the detection of ascenders, the practice trials were repeated.

The three stimulus conditions were presented in a counter-balanced order (ABCCBAABCCBA) but the requirements of the task remained constant across stimuli: participants pressed one key of a response box with their right hand index finger if one or more ascender was present and another key with their right middle finger if no ascenders were present. Rate and mode of stimulus presentation were as in Study 1, with each stimulus displayed for 1 s with a 2 s inter-stimulus interval. Reaction time and accuracy of response were recorded. rCBF was measured and analysed as reported above.

Results

Psychometric tests

As shown in Table 5, the dyslexic and control groups were well matched in terms of age and IQ. The dyslexics performed significantly worse than the controls on the WRAT reading and spelling tests [reading: $F(1, 10) = 12.0$; $P < 0.01$; spelling: $F(1, 10) = 24.1$; $P < 0.001$], and on the NART [$F(1, 10) = 17.0$; $P = 0.002$]. When reading single words

Table 5 Subject characteristics: reading and phonological abilities

Variable	Dyslexics (n = 6)		Controls (n = 6)		P
	Mean	SD	Mean	SD	
Age (years)	24.5	6.1	24.5	2.9	n.s.
<i>IQ tests (WAIS-R)</i>					
Full-scale	119.2	6.1	122.2	13.9	n.s.
Verbal	118.0	3.3	124.0	17.3	n.s.
Performance	115.5	11.6	114.0	10.2	n.s.
<i>Standardized literacy tests</i>					
Reading NART (errors; maximum = 50)	23.3	7.1	8.7	5.1	**
Reading WRAT (standardized scores)	103.8	8.6	117.7	4.6	**
Spelling WRAT (standardized scores)	89.8	12.5	117.7	6.0	***
<i>Single word/pseudoword reading</i>					
Accuracy (maximum = 40):					
words	39.5	0.8	40.0	0	n.s.
pseudowords	34.8	3.7	39.7	0.5	**
Latency [†] (ms):					
words	725.9	67.0	573.0	36.0	***
pseudowords	1405.0	195.0	817.1	154.0	***
<i>Phonological measures</i>					
Spoonerisms (errors; maximum = 12)	5.2	4.2	0.5	0.8	**
Spoonerisms (s/pair)	13.2	3.8	4.8	1.7	***
Phonemic fluency (words in 30 s)	20.3	3.4	27.0	5.4	*
Digit naming: 50 digits (s)	19.8	2.6	15.4	3.9	*
Auditory STM (mean correct; maximum = 6)	2.2	0.8	3.5	0.5	**
WAIS digit span (maximum = 19)	7.7	1.9	11.2	1.5	*

Stereotactic conventions as described in Table 3. Z scores significant at $P < 0.001$; n.s. = non-significant. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; [†]latency based on correct responses only.

the dyslexics were significantly slower than controls [$F(1, 10) = 23.8$; $P < 0.001$], although they were no less accurate ($P = 0.1$). The dyslexics' pseudoword reading was much slower than the controls' [by almost 600 ms; $F(1, 10) = 33.5$; $P < 0.001$] as well as less accurate [$F(1, 10) = 10.3$; $P < 0.01$]. No between-group difference emerged in response latency to a non-verbal dot stimulus. The dyslexics were also significantly impaired on the phonological measures tapping phoneme manipulation, naming speed and short-term memory.

Feature detection task performance during PET activation

Although the mean response latencies for the dyslexics (623 ms) were longer than for the controls (587 ms), this difference was non-significant ($P = 0.3$). No significant between-group difference was found for accuracy of detection ($P = 0.9$).

Regions of activation common to dyslexics and controls

Activations associated with the implicit processing of words and pseudowords are detailed in Table 6. In both groups of participants the presence of words/pseudowords

in the visual field elicited significant activations in the posterior superior temporal (BA 22), inferior frontal (BA 44/45/46) and medial frontal (BA 9) regions of the left hemisphere, and in the cerebellum bilaterally. The right precentral gyrus and thalamus were activated significantly more in the presence of words than false font. Pseudowords (relative to false font) activated the left posterior inferior temporal region (BA 37), left middle temporal region (BA 21), the left precentral gyrus, the cingulate and a left superior frontal region (BA 8). Greater activations in response to words relative to pseudowords were found for both groups in the right pre-central gyrus and a thalamic area. The converse comparison (pseudowords – words) highlighted activation of the left posterior inferior temporal region (BA 37), the left pre-central gyrus and a region of the cerebellum.

Areas of reduced activation for dyslexics, irrespective of word type

In general, the dyslexics showed less activation than controls in the left temporoparietal regions associated with reading. These differences reached significance in the posterior inferior temporal region (BA 37/20), the middle temporal cortex (BA 21), inferior parietal cortex (BA 40/7),

Table 6 Common areas activated by dyslexics and controls

Foci of activation	Words – false font				Pseudowords – false font				Words – pseudowords				Pseudowords – words				
	x	y	z	Z score	x	y	z	Z score	x	y	z	Z score	x	y	z	Z score	
Cerebellum	2	-64	-20	4.9	2	-68	-22	4.4									
Left posterior basal temporal	-2	-78	-20	3.8	-40	-50	-22	5.1					-42	-54	-20	3.0	
	-42	-48	-24	3.1	-46	-32	-26	3.6					-34	-38	-16	3.1	
					-48	-30	-12	3.3									
Left middle temporal (BA 20)	-60	-40	16	3.7	-66	-50	16	4.1									
Left superior temporal (BA 22)	-32	-32	10	3.6	-56	2	4	4.0									
Thalamus	12	-6	14	3.6				n.s.	14	-10	14	3.7					
	0	-20	0	3.5													
	-8	-44	0	3.1													
Bilateral precentral (BA 4/6)	58	0	44	3.2				n.s.	58	0	44	3.5					
Cingulate					-6	24	38	3.8									
Left inferior/middle frontal (BA 44/45/46)	-54	32	10	4.2	-50	30	12	5.0									
	-58	24	32	3.5	-56	18	26	4.1									
	-50	30	2	3.4	-50	34	28	3.1									
Left superior frontal (BA 8)					-48	6	26	4.0					-48	6	26	3.0	
					-50	4	48	3.2									

Stereotactic conventions as described in Table 3.

Table 7 Reduced activation for dyslexics during implicit reading, irrespective of word type

Foci of activation	Interaction				Main effects	
	x	y	z	Z score	Controls	Dyslexics
Left posterior basal temporal (BA 37) bordering cerebellum	-42	-50	-4	3.8	3.5	n.s.
	-42	-62	-14	3.1	4.2	n.s.
	-44	-76	-18	3.3	3.1	n.s.
Left inferior temporal (BA 20)	-46	-36	-24	3.1	5.0	n.s.
Left middle temporal (BA 21)	-48	-48	2	3.3	3.5	n.s.
Left inferior parietal (BA 40/7)	-40	-50	46	3.6	3.2	n.s.

Stereotactic conventions as described in Table 3. Z scores significant at $P < 0.001$; n.s. = non-significant.

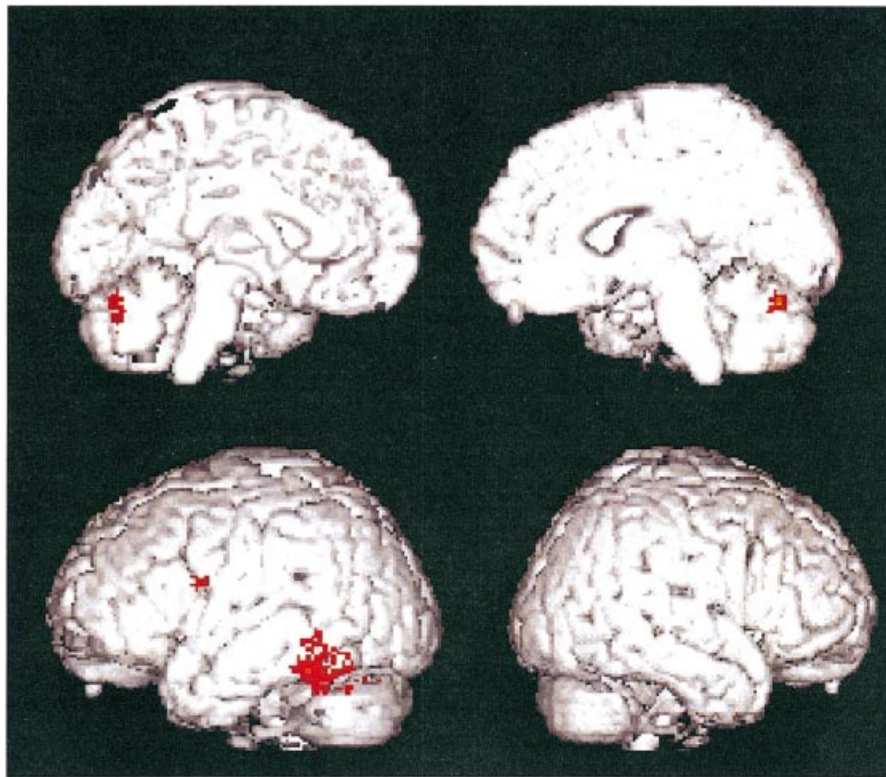


Fig. 2 Regions of reduced rCBF activation in the dyslexics relative to the controls across Studies 1 and 2, irrespective of word type. The dyslexics consistently activated the left inferior/middle temporal region, the left frontal operculum and the cerebellum to a lesser degree than the controls. As in Fig. 1, significant voxels are rendered onto lateral and medial surfaces.

and the cerebellum (see Table 7 and Fig. 2). There were no areas of increased activation for dyslexics.

Implicit and explicit reading: a combined analysis

Analysis of the combined data from studies 1 and 2 revealed regions of reduced activation in dyslexic readers relative to controls whether reading explicitly or implicitly (see Table 8). This analysis confirmed that both groups of dyslexic participants showed reduced activation in the left inferior/middle temporal region (BA 21/37), left frontal operculum and bilateral cerebellum.

Discussion

The psychological profiles of the dyslexic and control participants were highly similar to those from Study 1. They confirmed the persistence of reading and spelling difficulties in spite of performance levels that are in the average range for the total population. Thus, these students were compensated in the sense of showing greatly improved performance on literary tasks compared with their earlier difficulties, but they were not 'cured'. In particular, they showed significant impairments on orally presented phonological processing tasks.

The presence of words and word-like stimuli in the visual field during a feature detection task elicited widespread

Table 8 *Reduced activation for dyslexics, explicit and implicit reading combined*

Foci of activation	Interaction				Main effects	
	x	y	z	Z score	Controls	Dyslexics
Bilateral cerebellum	-18	-70	-28	3.0	5.7	n.s.
	10	-76	-18	3.3	5.8	n.s.
	-48	-48	-26	3.2	7.3	4.3
	-48	-60	-24	3.0	6.0	n.s.
Left inferior/middle temporal (BA 21/37)	-42	-60	-12	3.2	6.0	3.3
	-42	-48	-6	4.0	5.9	3.0
Left frontal operculum/anterior insula	-40	4	22	3.1	5.1	3.4

Stereotactic conventions as described in Table 3. Z scores significant at $P < 0.001$; n.s. = non-significant.

activation of the classical language areas, including the superior, middle and posterior temporal regions, the superior, medial and inferior frontal regions and the precentral gyri, in both the controls and the dyslexics. These activations indicate that the stimuli were processed even though the participants were not required to read them. The results from the controls replicate the results from the original feature detection study of Price and colleagues (Price *et al.*, 1996b) and are consistent with findings from a study of the passive viewing of real words (Price *et al.*, 1994). While the two groups shared a network of common activation, the normal readers demonstrated greater levels of activation in the temporoparietal regions of the left hemisphere. No differences between subject groups were detected in the cerebellum, thalamus or medial extrastriate cortex, as seen in Study 1.

Areas activated in common during implicit and explicit reading

The comparison of the two studies shows that reduced activation relative to controls in the left inferior temporal region (BA 37) and bilateral cerebellum was a consistent finding. The combined analysis also revealed that the left frontal operculum surrounding the most anterior part of the insula was less active in the dyslexic readers in both studies, although this was not detected as significant in the individual analyses reported above. A previous experiment has found that the left frontal operculum and the left posterior inferior temporal cortex are activated together during modality-independent naming, along with activation of the left thalamus, cerebellum and left posterior fusiform gyrus (Price and Friston, 1997). These regions have therefore been associated with lexical phonological retrieval. Reduced activation in these regions for the dyslexics relative to the controls is thus consistent with a deficit in retrieving lexical phonology. In the first study, the dyslexics showed increased activity in the left premotor cortex (Broca's area), some 2 cm more lateral to the opercular region showing reduced activation. When explicit reading was not required, activation in the left premotor cortex was not greater for dyslexic than

control readers. This was predicted from the hypothesis that the increase in left premotor activation reflects compensatory effort by dyslexics in order to decode print successfully for explicit reading (see Discussion for Study 1; for a similar account see Shaywitz *et al.*, 1998).

General discussion

The results from the explicit and implicit reading studies were highly consistent. The dyslexic and normal reader samples were very highly comparable across studies. Both groups of dyslexic readers showed impairments in literacy as well as in phonological tasks, despite a high degree of compensation. This pattern of results is similar to that seen in a large number of studies on developmental dyslexia (see review by Snowling and Nation, 1997). It does not rule out other deficits, for instance deficits in visual motion detection, which was not tested here (e.g. Eden *et al.*, 1996). The present findings confirm the persistence of subtle language processing difficulties even in those dyslexic individuals who attain high standards of literacy, compatible with tertiary education.

In Study 1 participants were required to read stimuli aloud, in Study 2 they were required to perform a task that did not explicitly require reading. In both cases, the level of performance was similar in the two groups. Irrespective of task requirements, both dyslexics and controls activated a common system of language areas when faced with print. The most important finding was that in both studies the dyslexics showed reduced activation in the left posterior inferior temporal lobe (BA 37) with corresponding reduction of activation in the left frontal operculum—two regions associated with modality independent phonological retrieval (Price and Friston, 1997). The reduced activation in regions that subservise phonological processing relates to the comprehensive phonological processing impairments displayed by the dyslexic participants during behavioural testing. However, while the behavioural tasks do not point to any specific aspects of phonological processing as being affected more than others, the neuro-imaging studies indicate

a selective impairment in regions associated with lexical phonological retrieval. Evidence supporting this claim is presented below.

What function has been ascribed to the left posterior inferior temporal gyrus where the dyslexics consistently showed reduced activation? This region has been shown previously to be active in normal readers during reading (Price *et al.*, 1996a), performance of a visual phonological discrimination task (Rumsey *et al.*, 1997), and picture, letter and colour naming (Price and Friston, 1997). In the latter study, activation in BA 37 was always accompanied by activation in the frontal operculum, a region that showed reduced activation in the dyslexics relative to controls in the combined analysis. The studies on normal subjects indicate that left BA 37 (and the left frontal operculum) are critical either in the specification or retrieval of phonological information irrespective of modality of access. The connections between the posterior inferior temporal region and Wernicke's area are normally strong (Di Virgilio and Clarke, 1997). In view of these connections and this region's role in the mediation of modality-independent naming, it has been suggested that BA 37 may be Wernicke's 'Wortschatz' (Luders *et al.*, 1991). The term 'Wortschatz', or thesaurus, implies an access facility to names of words and can be seen as a precursor of the more modern concept of the internal lexicon, and in particular, Morton's output logogen system (Morton, 1980). In support of this hypothesis, neuropathological data indicate that lesions in the posterior inferior temporal area lead to anomia in the absence of impaired object recognition (Foundas *et al.*, 1998).

What role does Wernicke's Wortschatz play in the reading process? If these regions are critically involved in lexical retrieval, they may have a special role in the lexical retrieval process during reading. This process is particularly crucial in English given the ambiguity of grapheme-to-phoneme mappings. A model of how the ambiguity may be resolved is provided by Berent and Perfetti's two-cycles process (Berent and Perfetti, 1995): essentially, a consonant skeleton is derived first, in bottom-up mode from grapheme to phoneme. This can be done since consonants have relatively reliable letter-to-sound mappings. Vowels, on the other hand, do not, and need to be resolved in context. Hence top-down lexical processes are needed to derive the correct vowel sound in a second processing cycle. Thus, the reduced activation of the lexical components of the language processing system in dyslexics could be a consequence of a general slowness of the recognition process. This would mean that the mapping between sublexical and lexical processes is delayed and hence relatively more effort appears to be demanded of sublexical processes, as indicated by the increased activation during reading aloud in a region associated with articulatory planning.

The finding of significantly reduced activation in the left posterior inferior temporal region (BA 37) in dyslexics is validated by its replication across two different studies with different subjects and different reading tasks. It is also

consistent with previously reported anomalies in the activation of posterior inferior temporal region of dyslexics during reading. The MEG study by Salmelin and colleagues, for example, reported a failure of impaired readers to activate this region during the first 200 ms after the presentation of a word, while control readers showed strong posterior inferior temporal activations (Salmelin *et al.*, 1996). Likewise, Rumsey and colleagues observed significant deactivations in the middle and inferior temporal gyri of dyslexics, but not of controls, during reading relative to fixation (Rumsey *et al.*, 1997).

Could the reduced activation of the area identified as Wernicke's Wortschatz in dyslexics point to a specific impairment in lexical processing? Although there is much evidence for difficulties in sublexical phonological processing (seen in the present study, for instance, in the Spoonerism task), there is also evidence for difficulties in lexical processing (seen in the present study, for instance, in poorer verbal fluency). The notion of a lexical impairment is also supported by existing behavioural data. Word finding difficulties are frequently seen in dyslexic children (Snowling *et al.*, 1988), particularly on tasks requiring rapid naming (Denckla and Rudel, 1976; Bowers and Swanson, 1991; Wolf, 1991). Such a finding was reported recently by Swan and Goswami, who found picture naming deficits in dyslexics and in 'garden variety' poor readers relative to chronological and reading-age matched controls (Swan and Goswami, 1997). Unlike the garden variety poor readers, the dyslexics were often unable to name pictures that they could recognize; this would point to a specific difficulty in retrieving the phonological codes that correspond to the items to be named. The present findings are therefore consistent with dyslexia involving a core deficit in accessing phonological word forms.

Whether this deficit is itself a primary source of the failure of the system, or whether system failure, in terms of weak connectivity between otherwise well-functioning components, causes name retrieval to be slow, remains an open question. An answer would require a demonstration that dyslexics can activate BA 37 normally in the context of a different neural system. For instance, Paulesu and colleagues demonstrated that developmental dyslexics were able to activate Broca's area during rhyming and the left temporoparietal cortex during a short term memory task, but in contrast to normals, these areas were not activated in concert (Paulesu *et al.*, 1996). Paulesu and colleagues concluded that Broca's area and the left temporoparietal cortex were functioning normally but in a disconnected fashion, perhaps due to weak connectivity between anterior and posterior regions. In other words, no single component of the system may be malfunctioning, but the system as a whole is malfunctioning because the components do not work in concert. A similar account might underlie the abnormal activations we observe in the present study, but further experiments are required.

Finally, a somewhat disappointing aspect of our studies was that no striking differences were shown between reading

words and pseudowords. Any differences shown were simply those of greater activation of the same areas for the pseudowords compared with the words. This was true for both normal and dyslexic readers and may possibly reflect the high degree of lexical ‘credibility’ of the pseudowords used. It is plausible that the reader would engage in a lexical search for an existing entry. Interestingly, previous PET studies have also indicated few differences in the reading of words and word-like stimuli in normal readers (Price *et al.*, 1996b) and dyslexics (Rumsey *et al.*, 1997) where different types of non-words were used. The systematic manipulation of similarity between words and non-words remains a task for the future.

In summary, despite the high level of compensation that dyslexics can reach in reading and writing skills, their difficulties persist at the cognitive level. This is reflected in the dyslexics’ patterns of brain activation and in their performance on the more taxing phonological tasks at the behavioural level. Our findings, which pinpoint the deficit to the neural system underlying lexical retrieval, demonstrate the utility of functional neuroimaging studies of developmental disorders when the behavioural manifestations of the disorder have ceased to be clinically abnormal.

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Appendix 1

Word recognition tasks

In this test four blocks each of 20 words or pseudowords were presented in an ABBA order; the first block comprised pseudowords. The words were highly concrete (>520 on the Kucera–Francis database) and highly familiar (> 450 on the Kucera–Francis database) nouns. They were also as regular as possible in terms of grapheme–phoneme conversion. Within each block half of the stimuli were two syllables in length and half had three syllables. Words with strong onsets, such as plosives, were favoured while sibilants and fricatives were avoided. Pseudowords were created from these words by maintaining the onset and coda while changing internal consonants. Examples of the words and corresponding pseudowords include: carrot, table, garden, pencil, vinegar, corridor, microscope, monument; cassot, tagle, garlen, pectil, vipelar, collipor, mibrostope and mofukent.

Words and pseudowords were presented individually with the SuperLab program. Stimuli were presented in black capitals (Times, 48 point size font) in the centre of the computer screen, against a white background. A six letter word such as ‘rabbit’ measured ~7 cm. Each word was displayed for a maximum of 3 s. Participants were asked to read each word/pseudoword as soon as it appeared on the screen. Once the subject had responded and the latency had been recorded via a voice key, the word disappeared; there was a 1-s interval before the next stimulus was presented.

Spoonerisms

The Spoonerism task involves the segmentation and manipulation of the constituent sounds of words (Perin, 1983). The 24 words used in the Spoonerism task were two syllable highly familiar concrete words selected on the basis that they had clear syllable divisions (e.g. BAS-KET) and no consonant clusters in their onsets. No real words were produced by recombining the onsets and rhymes of the pairs of words (see below):

Word 1:	Word 2:	Spoonerisms:
Basket	Lemon	Lasket/Bemon
Button	Turtle	Tutton/Burtle
Doctor	Window	Woctor/Dindow
Fabric	Pocket	Pabric/Focket
Motor	Tiger	Totor/Miger
Mustard	Salad	Sustard/Malad
Novel	Table	Tovel/Nable
Paper	Satin	Saper/Patin
Rabbit	Sofa	Sabbit/Rofa
Radish	Garlic	Gadish/Rarlic
Razor	Medal	Mazor/Redal
Ribbon	Silver	Sibbon/Rilver

Prior to the test, the concept of Spoonerisms was introduced and defined in the following way: ‘A Spoonerism is where you have two words and you swap over the beginning sounds of each word to make two new words or pseudowords. For example, the words RED/PEN become PED/REN. Can you hear what I’ve done? I’ve taken the /r/ sound from RED and the /p/ sound from PEN and swapped them around to produce PED/REN’. A couple of practice trials followed this introduction as participants were asked ‘What do the words DESK/HAT become?’ If subjects responded correctly, ‘HESK/DAT’, they were told that this was correct and they were given the second practice trial, ‘FISH/BOX’. Responses were scored as correct only when the word order was maintained in the response. In response to the words BASKET/LEMON, for example, the subject must respond with ‘LASKET/BEMON’; the response ‘BEMON/LASKET’ would not be allowed. If subjects made errors during practice they were given feedback and a further trial. Word order errors were corrected during the test only the first time they occurred.

Time taken to complete the test was recorded with a stopwatch from just before the first pair was given until the last Spoonerism was completed. The time taken per pair was calculated by dividing this time by 12. During the task the stopwatch was stopped in the event of any interruptions from

outside and during correction of the subject. In the event of hesitation or repeated attempts timing continued. One repeat by the experimenter was allowed per word pair if requested, but timing continued during this repetition. If the subject experienced real difficulty and discomfort the task was discontinued at the discretion of the experimenter.

Phonemic fluency

Participants were first given a practice trial of semantic fluency ('how many animals can you think of in 30 seconds?'), then the phonemic fluency task was introduced. Participants were asked to think of as many words as possible beginning with a particular sound ('list as many words as you can beginning with /s/; when I say 'begin' . . . Okay? . . . 'Begin' . . .'). On saying 'begin' the stopwatch was started; after 30 s the subject was stopped. The task was repeated for words beginning with /f/. The phonemic fluency score was calculated from the mean number of words generated across these two trials.

Auditory short-term memory for short and long words

Before testing, participants were shown the words to be used in the task. These were seven short words (worst, sum, yield, harm, bond, hate, twice) and seven long words (immediately, university, organization, individual, opportunity, association, representative), taken from Baddeley *et al.* (1975). Participants were asked to read the words aloud before they

were removed from view. Two practice trials were then given in which, as in the experimental trials, participants heard lists of six of the words spoken at the rate of one word every second; as soon as the experimenter had spoken the last word from a list the participant was prompted to recall the words in the order of presentation. If a word could not be remembered participants were told to use the word 'something' to maintain the order of the surrounding words. Only words recalled in the appropriate position were scored as correct. Ten lists of short words and 10 lists of long words were presented in alternating order, and the number of words recalled correctly was summed across the two lengths of list.

Digit naming

In this task participants were asked to read aloud, as fast as possible, strings of 50 single syllable digits (the number 7 was excluded as the only digit with a two syllable name). Digits were presented in blocks of five (e.g. 68248 83542 99634), although participants were told to read each digit as a single number, i.e. the string 51368 should be read as 'five, one, three, six, eight'. The task was presented twice with different strings of 50 digits. The time taken to read each string was recorded with a stopwatch, starting from the experimenter saying the word 'go' of 'ready, steady, go', until the last digit had been said. Accuracy of reading the digits was monitored by the experimenter although it was not scored. When participants (rarely) made mistakes, they always self-corrected immediately; any repetitions were included in the timing. A mean score, in seconds, was obtained over the two trials.