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# An fMRI study of the differential effects of word presentation rates (reading acceleration) on dyslexic readers' brain activity patterns

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## Abstract

Several lines of evidence have recently provided a clear indication that word reading rate can be considered as an independent variable which influences comprehension as well as accuracy in reading. Thus, not only is fluent reading a critical characteristic of skilled (automatic) reading, it has been shown that faster reading does not necessarily incur a cost in terms of accuracy. Indeed, readers of various levels of reading proficiency, as well as clearly impaired readers (dyslexics), if made to read faster than their normal (routine) reading rate, can increase their decoding accuracy and comprehension. Using block design, blood-(de)oxygenation-level-dependent (BOLD) functional magnetic resonance imaging we studied the differences in brain activation patterns induced by reading and script processing in adult dyslexics and normal reading controls as a function of two word presentation rates. Word presentation rates were set individually for each participant to correspond to his/her routine reading rate (slow) and to a correspondingly faster rate (fast). Three task conditions were tested: sentences (plausibility judgment), single words (concrete/abstract judgment), non-words (homophonic judgment). Comprehension and accuracy in the faster presentation rates were unimpaired in both groups. There were no significant differences between the activation patterns induced in both groups in 'slow' reading of sentences and single words,

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46 but 'fast' reading was related to higher activations in visual areas in the normal readers. However, in  
47 the slow non-words condition the dyslexics were characterized by activations in the Lt IFG (Broca's  
48 area) and operculum, while the control dyslexics clearly activated visual processing areas (extra-striate  
49 cortex). These differences in brain activation patterns were not found in the fast non-words  
50 condition. We propose that time-constrained (accelerated) script decoding may prompt the dyslexic  
51 brain to process graphemic information in a different manner compared to the one employed in  
52 unconstrained (routine) reading, in some conditions in a manner of processing much closer to the one  
53 employed by normal reading controls.

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55 *Keywords:* Reading acceleration; Acceleration phenomenon; Dyslexia; Functional brain imaging; Word  
56 presentation rates; Visual areas; Inferior frontal region

## 57 58 **1. Introduction**

59  
60 Developmental dyslexia has a high incidence (5–17%) among school-age children,  
61 occurs in most known languages and results in a considerable disability in literate societies  
62 because the reading deficits persist into adulthood (Shaywitz et al., 1998, NEJM). A recent  
63 report on dyslexia and literacy (British Psychological Society (BPS), 1999) proposed the  
64 following working definition of developmental dyslexia: 'Dyslexia is evident when  
65 accurate and fluent word reading and/or spelling develops very incompletely or with great  
66 difficulty'. The Health Council of the Netherlands stresses the inability to attain  
67 'automatization', i.e. effortless, fast and accurate word identification, in dyslexics. Thus, in  
68 the view of both these experts' panels, poor readers are characterized by non-fluent, slow  
69 and inaccurate word reading (Kame'enui, Simmons, Good, & Harn, 2001; Torgesen,  
70 2000; Wolf, 2001; Wolf, Bowers, & Biddle, 2000).

71  
72 The emphasis on both accuracy and fluency reflects several changes in the current  
73 understanding of dyslexia (see Wolf (2001) for review) including a change in the common  
74 perspective that reading fluency is a result of the effectiveness of phonological processing  
75 (Lyon & Moats, 1997). Given the notion that normal reading acquisition could be  
76 conceptualized as the acquisition of non-linguistic skills (Bitan & Karni, 2004; Karni &  
77 Bertini, 1997) one may consider the possibility that gains in speed and gains accuracy in  
78 the performance of a given task may represent different aspects of knowledge (Hikosaka  
79 et al., 2002). Indeed, an improvement in both speed and accuracy with practice, rather than  
80 speed accuracy tradeoff, is a recognized characteristic of skill acquisition (procedural  
81 learning) in both motor and perceptual domains (Karni, 1996; Karni et al., 1998) although  
82 there may be phase differences in the attainment of these two parameters of performance  
83 (Korman, Raz, Flash, & Karni, 2003). The notion that skilled reading evolves in a manner  
84 similar to the acquisition of non-linguistic skills further suggests that there may be  
85 qualitative differences in the way the reading task is accomplished at different levels of  
86 accumulated experience with reading (and specific lexical items)—i.e. that different levels  
87 of brain representations may sub-serve word recognition at different stages of experience  
88 (Bitan & Karni, 2003; Clark & Wagner, 2003; Ofen-Noy, Dudai, & Karni, 2003; Papagno,  
89 Valentine, & Baddeley, 1991; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003; and  
90 see, for example, in non-linguistic, motor, tasks, Korman et al., 2003; Sosnik, Hauptmann,

91 Karni, & Flash, 2004). The notion that similar basic neural mechanisms underlay the  
92 acquisition and retention of non-linguistic and linguistic skills (Bitan & Karni, 2003; Karni  
93 & Bertini, 1997) further suggests that the ability to employ skilled reading routines may be  
94 specific for, and thus critically dependent on, the task pertaining to the words being read  
95 (Bitan & Karni, 2004), and even on simple physical aspects of the script presentation such  
96 as word presentation rates. This latter notion is in line with the proposal by Tallal and  
97 co-workers of a rather basic (low-level) multi-sensory processing deficit in dyslexia,  
98 whose core is difficulties in time-constraint perception, in dyslexics (Merzenich et al.,  
99 1996; Stein, 1991; Tallal, 1980; Tallal et al., 1996; Zeffiro & Eden, 2000).

100 There is growing support for the notion that word reading fluency may reflect sub-  
101 processes other than phonology and can thus be conceptualized as a separate factor for the  
102 reading deficit (Breznitz, 2002; Kame'enui et al., 2001; Wolf & Bowers, 2000). Recent  
103 data indicate the presence of a possible second core deficit (in addition to phonology) in  
104 dyslexia, measured as naming-speed deficits (Denkla & Rudel, 1976; Wolf, 1997, 1999;  
105 Wolf & Bowers, 2000; Wolf et al., 2000) and/or speed of processing deficits (Breznitz,  
106 1997a,b, 2002) related to both fluency and comprehension problems. Some reading  
107 intervention studies have also indicated that while intensive training in phonemic  
108 awareness could improve decoding and word identification in poor readers, there were  
109 only minimal gains in reading fluency (Lyon & Moats, 1997; review see Meyer and Felton  
110 (1999)). Moreover, cross-linguistic data suggest that in languages with an irregular  
111 orthography, reading fluency poses the primary difficulty in regular orthographies  
112 (Wimmer & Mayringer, 2000; Wimmer, Mayringer, & Landerl, 1998). Experimental  
113 findings, from studies conducted in the last decade or so, have provided a clear indication  
114 that word reading rate can be considered as an independent variable which influences  
115 comprehension as well as accuracy in reading (Breznitz, 1997a,b, 2001, 2002).

116 Support for the notion of fluency as an independent parameter in reading has come  
117 from the recently described, rather paradoxical, 'acceleration phenomenon' (Breznitz,  
118 2001, 2002). The basic finding, in multiple experiments, was that native Hebrew, and  
119 native English, readers of various levels of reading ability, as well as clearly impaired  
120 readers (dyslexics), if made to read, about 10–20%, faster than their normal (routine)  
121 reading rate, increase their decoding accuracy and comprehension (Breznitz, 1997a,b,  
122 2001, Breznitz, DeMarco, & Hakerem, 1993; Breznitz, DeMarco, Shammi, & Hakerem,  
123 1994; Breznitz & Leiken, 2000; Breznitz & Share, 1992). The experimental set-up in all  
124 the above studies, constituted of a unique, and certainly unusual, script presentation  
125 method which constrained reading time: one in which the target script (words, sentences)  
126 was erased off the screen, letter by letter in the direction of reading, at a set rate. While the  
127 neurological substrates of this effect are not known, there are indications that the  
128 acceleration procedure can be conducive to extended attention span and reduced  
129 distractibility, as well as enabling the readers to surmount some of the limitations of short-  
130 term memory (Breznitz, 1997b; Breznitz & Share, 1992). Several other cognitive  
131 mechanisms were proposed, including enhanced word retrieval from the mental lexicon,  
132 and there are some suggestions that the acceleration procedure enabled dyslexic children  
133 to partially surmount their phonological deficits (Breznitz, 1997a, 2002).

134 These data provided a basis for considering the proposition that accelerated reading  
135 may prompt the dyslexic brain to process graphemic information in a different manner

136 from the one engaged routinely (i.e. when no time constraints are induced by the script  
137 presentation system). It should be noted, however, that the degree to which dyslexics can  
138 use this alternative reading mode may be rather limited and depend on the very specific  
139 script presentation system described above. Initial support for the alternative reading mode  
140 conjecture was found in combined behavioral and electrophysiological (event related  
141 potentials, ERP) studies wherein sub-lexical (e.g. letters, visual patterns) and various  
142 lexical stimuli were presented to adult dyslexic and normal readers at different  
143 presentation times. These studies (Breznitz, 2002; Breznitz et al., 1993; Breznitz &  
144 Leiken, 2000; Leiken & Breznitz, 1999) showed that fast paced stimulus presentations  
145 resulted in significantly enhanced accuracy in both discrimination and recognition tasks in  
146 dyslexic readers. Moreover, in both normal reading and dyslexic individuals, ERP  
147 latencies (P200 and P300) were found to appear earlier in the fast as compared to the slow  
148 presentation condition. However, latency differences between the two presentation  
149 conditions were more pronounced in the dyslexic individuals. Surprisingly, the ERP  
150 components were spatially distributed in a differential manner in the two groups as a  
151 function of acceleration (Breznitz et al., 1993; Breznitz & Leiken, 2000; Leiken &  
152 Breznitz, 1999)

153 There is accumulating support for the notion that different routines for reading are  
154 employed in the dyslexics' as compared to normal readers' brains from recent studies  
155 using imaging techniques such as fMRI and PET (Shaywitz et al., 1997, 2003; Zeffiro &  
156 Eden, 2000). Several studies have specifically addressed the issue of brain regions that  
157 sub-serve the process of normal reading (Demonet, Price, Wise, & Frackowiak, 1994;  
158 Petersen & Fiez, 1993; for a recent review, see Zeffiro and Eden (2000)) and there are  
159 many indications that although differently selected participants, and different tasks,  
160 languages and reading materials, were studied in the different studies, dyslexic readers  
161 may rely on the engagement of different brain areas compared to normal readers, given the  
162 same task. One seminal study has suggested that dyslexic readers may exhibit a functional  
163 disruption in a broad system comprising the posterior cortex encompassing visual and  
164 language areas, as well as parts of the parietal association cortex (Shaywitz & Shaywitz,  
165 1999) and may more heavily rely on left inferior frontal cortex compared to normal  
166 reading controls. Several studies have shown significant brain activity differences between  
167 dyslexic and normal readers while performing phonological and other script decoding  
168 tasks (Paulesu, Frith, Snowling, & Gallagher, 1996; Pugh et al., 2000; Shaywitz et al.,  
169 1998). Simos et al. (2002) have recently studied the brain activation patterns in the brains  
170 of dyslexic individuals using MEG measurements, before and after intensive training on  
171 phonological tasks. Their main findings were that before training the dyslexics' brains  
172 showed little or no activation in the posterior superior temporal gyrus (STGp) an area  
173 normally involved in phonological processing. However, after phonological training, the  
174 activity in the STGp increased by several orders of magnitude in every dyslexic  
175 participant.

176 Although somewhat simplistic and in no way exhaustive or conclusive a possible  
177 summary of a number of different brain imaging studies is that compared to normal readers  
178 dyslexics display relatively less engagement of posterior visual and language regions and  
179 relatively more activation in anterior language regions when performing tasks that  
180 make progressively greater demands on phonological analysis (Paulesu et al., 1996;

181 Shaywitz et al., 1998; Zeffiro & Eden, 2000). One should note that most published studies  
182 were concerned with dyslexia in English which may be considered rather as an outlier  
183 orthography (Share, 2003) and also that most studies were concerned with adult dyslexics,  
184 mainly because of methodological complexities associated with developmental brain imaging  
185 studies wherein children must participate (Gaillard et al., 2001; Turkeltaub et al., 2003).

186 The current study was designed to investigate the conjectured possibility that time-  
187 constrained reading (acceleration) may enhance reading effectiveness among dyslexic  
188 readers by prompting the dyslexic brain to process graphemic information in a manner  
189 different from the one engaged routinely (i.e. when no time constraints are imposed by the  
190 script presentation system) in reading. The results suggest that while in some reading tasks  
191 the difference between the two reading groups became significant, a manner of script  
192 processing much closer to the one employed by normal reading controls was invoked,  
193 given time constraints, in a script decoding task, using non-lexical items, by well  
194 compensated adult dyslexics.

## 195 196 197 **2. Methods**

### 198 199 *2.1. Participants*

200  
201 Male university students, 8 dyslexic and 8 age matched normal readers, participated in  
202 the study. The two groups were also matched on nonverbal IQ scores (Raven standard  
203 progressive matrices, Raven, 1960). All subjects were right handed with normal or  
204 corrected-to-normal vision and with no neurological deficiencies. The participants' ages  
205 ranged from 22 to 25 years (mean age 23 years and 5 months, SD=0.10). All were native  
206 Hebrew speakers and were paid for their time participating in the study. The dyslexic  
207 readers were recruited through the University Student Support Service of the University of  
208 Haifa having been diagnosed as dyslexic in childhood and found to be impaired readers by  
209 the Student Support Service.

210 *Table 1* summarizes the main behavioral measures characterizing the two groups.

211 IQ was assessed using the Raven standard progressive matrices (Raven, 1960). Several  
212 tests were used to obtain estimates of reading accuracy, reading time and comprehension.  
213 *Decoding skills: One Minute Tests (Shatil, 1997a,b)*. This battery included two subtests in  
214 which subjects were asked to read lists as quickly and accurately as possible within the  
215 space of 1 min. The first list contained 100 real words arranged in order of increasing  
216 length (1–5 syllables) and decreasing frequency, and the second list was comprised of 100  
217 pseudo-words arranged in order of increasing length (1–5 syllables). Scores were based on  
218 the number of words and pseudo-words read correctly. In order to obtain a comprehensive  
219 decoding score, Z-scores were first calculated for each of the lists separately and then  
220 combined to give a total Z-score for decoding performance. *Reading comprehension,*  
221 *accuracy and speed in context:* the reading performance for text was measured using two  
222 texts from the reading test section of the Israeli Psychometric SAT (*The Center for*  
223 *Psychometric Tests, 1994*). Each text contained a short story (17 sentences, 257 words  
224 each), which appeared in its entirety on the computer screen. Reading time was measured  
225 by requiring a button press upon beginning to read and again upon conclusion.

Table 1  
Behavioral baseline measures

Test	Control		Dyslexic		Group comparison, <i>t</i> (1,15)
	Mean	SD	Mean	SD	
Raven matrices (raw scores)	52.1	3.62	51.65	3.81	NS
Decoding, Z-scores (words, pseudo-words and connected text)	1.01	1.23	−1.52	1.66	3.03**
Reading time-connected text (in s)	81.12	15.36	101.1	30.01	2.61**
Comprehension connected text (out of 6)	5.69	1.34	5.01	1.71	NS
Phonological accuracy (out of 40)	37.3	3.09	24.2	15.87	3.90**
Phonological time (in s)	99.07	5.36	146.2	7.36	3.44**
Orthographic processing: parsing test—accuracy (out of 50)	48.72	2.94	36.77	4.07	3.73**
Orthographic processing: parsing test—time (in s)	167.91	5.23	276.84	23.16	3.23**
Working memory completion (out of 10)	5.67	0.56	4.33	0.75	3.21**
Working memory opposites (out of 10)	6.89	0.83	4.95	0.91	3.47**
Total word production fluency	47.81	5.43	33.65	6.43	3.32**
% WAIS digit symbols (percent accuracy)	100%	6.01	78%	8.65	3.63**
WISC-R symbol search (speed)	59.48	7.51	46.76	9.66	3.13**

\* $p < 0.01$ , \*\* $p < 0.001$ .

When reading was completed, the text disappeared from the screen and six multiple-choice questions appeared one at a time. One of the two stories was read orally and decoding errors were recorded to obtain a measure of accuracy. Comprehension scores were based on the total number of correct answers across the two texts. Reading time scores were determined on the basis of the mean reading time across both texts. *Phonology* (The Phoneme Recognition Test for Words and Pseudo-words, Ben-Dror & Shani, 1996). This test included two sections, each containing 20 words. In the first section, the experimenter read each word and pronounced a syllable within the word. The subject had to produce the word obtained by omitting the specified syllable. In the second section, the experimenter read each word aloud and specified a phoneme located at the beginning, middle or end of the word. The subject had to produce the pseudo-word obtained by omitting the designated phoneme. Scores were based on the total number of accurate responses and test performance time of the two subtests. *Orthography: Parsing Test* (Breznitz, 1997). In this test, 50 rows of 4 words each were presented as a continuous line of print (i.e. no blank spaces). The subject was asked to draw lines to indicate where between-word spaces should be. Scores were based on performance accuracy and total test performance time.

In addition, working memory was assessed using the *Opposites* test (Shani & Ben-Dror, 1998b) in which a sequence of adjectives, each of which has an opposite (for instance, tall/short; big/small; black/white) were presented in an order of increasing series length. The set of adjectives was read aloud by the examiner and the participant was required to respond with the opposite of each adjective in the series, in the order in which the adjectives were presented (e.g. the response to ‘tall—big—black’ would be ‘short—small—white’). The examiner continued until the subject failed two consecutive adjective

271 sequences within the same set. The test was not time-limited, and scores were based on the  
272 number of correct responses. *Working Memory-Completion* (Shani & Ben-Dror, 1998a).  
273 This test was comprised of sets of sentences in which the final word was missing. The  
274 number of sentences in each series ranged, in ascending order, from 2 to 5. The examiner  
275 read each sentence aloud, and the participant was required to complete the missing word in  
276 the sentence. At the end of a particular set of sentences, the subject was asked to recall the  
277 completing words in the order in which they appeared. Each set contained two series of  
278 sentences. The test was continued until the subject failed two consecutive series. The test  
279 was not time-limited, and scores were based on the number of correct responses. Word  
280 Fluency Test (Breznitz, 1996; designed on the basis of Lezak (1993)). Participants were  
281 requested to generate two lists of words each beginning with a given letter ('resh' (r), and  
282 'shin' (s)) and then a list of groceries. One minute was allotted for each list. The score was  
283 the sum of the words recalled in the three tasks.

### 284 285 286 **3. Procedure & methods (fMRI)**

#### 287 288 *3.1. Behavioral tasks*

##### 289 290 *3.1.1. Stimuli*

291 The stimuli were Hebrew words presented (throughout the experiment) one at a time at  
292 the center of the display. Stimulus durations were set individually for each individual  
293 participant to correspond to his/her routine reading rate (slow) and to a correspondingly  
294 faster rate (fast) (e.g. 200 and 300 ms, respectively). The 'slow' rates corresponded to very  
295 comfortable stimulus duration rates, about up to 20% slower than the rates previously  
296 determined in the baseline (self paced) measurements of the reading acceleration task  
297 (Breznitz, 1987). The slow presentation rates for each individual were set to ensure a level  
298 of performance on the task of more than 90% correct in a pre-test, and without any loss in  
299 accuracy in the 'fast' presentation rate. This procedure resulted in three different stimulus  
300 duration rates per item in each of the tasks.

##### 301 302 *3.1.2. Tasks*

303 There were three reading related tasks, each presented in two presentation rates.

304 *Single words (SW)*. Subjects were required to make a semantic judgment  
305 (abstract/concrete) on Hebrew nouns of medium high frequency, each 3–6 letters long.  
306 The timing (stimulus duration) times were either 200, 300 or 550 ms for each word and a  
307 patterned mask (three superimposed 6 letter non-words) immediately followed for twice  
308 the target word presentation time. Each word was presented once with a stimulus onset  
309 asynchrony of 2 s, i.e. at a rate of 1 word (and corresponding mask) every 2 s.

310 *Non-word (NW)*. Subjects were required to indicate (in a two alternative forced choice)  
311 whether each target pseudo-word contained two similarly sounding elements (phonolog-  
312 ical judgment). Each display item consisted of a single pronounceable non-word made of  
313 three distinct Hebrew phonemes. Half the target pseudo-words contained two identical  
314 phonemes but with non-identical orthography (a redundancy possible in Hebrew). Thus,  
315 the task required effective grapheme-to-phoneme translation for non-lexical words.

316 The timing options were 400, 600, or 800 ms per target item durations and each target item  
317 was immediately followed by a patterned mask (three superimposed non-words of  
318 corresponding letter length) for twice the duration of the target item. Each pseudo-word  
319 was presented at a rate of 1 every 2.4 s.

320 *Sentence reading (SNT)*. Subjects were required to make a plausibility judgment (in a  
321 two alternative forced choice) on simple sentences each made of four to six words  
322 presented one at a time. The timing options were 400, 550 or 650 ms per single word  
323 duration with a fixed between-words delay of 300 ms. The between sentence intervals  
324 were adjusted to maintain a mean rate of one sentence every 3 s.

325 A verb generation (VG) task was used as an independent means for defining language  
326 laterality as well as the extent of classical language areas (Broca's and Wernicke's areas).  
327 In this task condition, the participants were required to silently generate a verb associated  
328 with the presented (target) nouns. Each target noun was presented for 800 ms without  
329 masking, however the targets were presented in one of two rates: 1 noun every 2 or 1  
330 every 3 s.

### 331 3.1.3. Behavioral pre-test

332 Immediately before the imaging session each participant was given explicit instruction  
333 on the various tasks and then retested, in each task, to determine the individual setting of  
334 the stimulus presentation (target and mask duration) times during scanning.

### 335 3.2. MR brain imaging

336 A 2T-magnet system (Prestige, Elscint, Israel) equipped with echo-planar imaging  
337 capabilities was used. All studies were conducted at the MRI unit of the Division of  
338 Diagnostic Radiology at the C. Sheba Medical Center, Tel-Hashomer.

#### 339 3.2.1. Scanning

340 During scanning subjects were supine in the magnet, with their heads immobilized by  
341 foam pads, and viewed the back-projected (computer controlled) stimuli through a mirror  
342 device. Responses were given using the dominant index finger. Tasks were administered in  
343 a pseudo-random order across subjects. Each task was presented in the two speed levels  
344 (fast and slow) and each task condition was repeated twice using a different word list for  
345 each repetition. Thus, the total number of experimental runs, per participant, were 14  
346 (3 tasks  $\times$  2 timing conditions  $\times$  2 repetitions per condition (versions) + 2 repetitions of the  
347 VG task).

#### 348 3.2.2. Imaging parameters

349 T1 weighted, high-resolution, anatomical images were acquired for each participant,  
350 and used to determine the outline of regions of interest (ROIs) based on anatomical  
351 landmarks. For the functional brain imaging studies a gradient-echo EPI sequence (TR,  
352 3000 ms; TE, 48 ms; flip angle, 90) was used to acquire 14  $\times$  5 mm contiguous axial slices  
353 with the middle of the 4th slice aligned with the AC-PC line. In-slice resolution in the  
354 functional data was 3  $\times$  2.67 mm (matrix size of 58  $\times$  72). Thus, although the scanned  
355 brain volume included all structures from -17.5 mm below, and extending dorsally to  
356

361 52.5 mm above, the AC–PC plane, brain areas such as the dorsal aspect of the dorso-lateral  
362 prefrontal cortex, the dorsal parietal lobe and some ventral temporal lobe areas were not  
363 visualized.

364

### 365 3.2.3. *Set (session) design*

366 An alternating block design was used for all conditions and tasks with two task  
367 performance epochs (both of the same condition) alternating with three baseline epochs  
368 (fixation only). Forty-four time points (scans) were acquired in each set (baseline-task-  
369 baseline-task-baseline, 12-8-8-8-8). There were 10 non-words (and masks) and 12 single  
370 words in each task interval (block) in the NW and SW conditions, respectively.

371

372

### 373 3.3. *Data analysis*

374

375 Statistical analysis was performed using the general linear model as implemented in  
376 SPM99 (SPM99, Institute of Neurology, London).

377

#### 378 3.3.1. *Spatial pre-processing*

379 Due to scanner specific image distortions the standard MNI (Montreal Neurological  
380 Institute) SPM99 brain templates were not used as reference images. Instead a study  
381 specific template brain was generated from data from all participating subjects' brains  
382 using the SPM99-16 built-in software tools. In brief, the procedure included: creating a  
383 mean image for each subject (anatomical and EPI data); zero padding with a two-voxel  
384 layer in the coronal plane to avoid voxel losses; spatial co-registration using mutual  
385 information and re-slicing in 15 steps so as to telescope the data into the largest  
386 participant's brain; calculation of a new mean image and smoothing with a 10 mm  
387 Gaussian kernel.

388 For the anatomical template similar steps were involved: co-registration using mutual  
389 information of each anatomical scan to the non-smoothed version of the newly created EPI  
390 brain template; calculation of a mean anatomical image from the co-registered scans;  
391 normalization of the co-registered scans to this mean anatomical image; and creation of a  
392 new mean anatomical template from all the normalized anatomical scans. An additional  
393 segmentation and brain extraction stage followed by manual adjustments was performed  
394 in order to obtain an as optimal as possible three-dimensional model of the normalized  
395 brain space for data visualization.

396 The spatial normalization of the fMRI data sets required in most of the 16 cases the  
397 inclusion of a subject specific 'object masking' image file obtained by segmentation and  
398 brain extraction of the individual mean fMRI image (acquired during the realignment  
399 procedures) followed by a smoothing step (8 mm kernel size). Thereafter, subject specific  
400 normalization and non-linear regularization parameters were determined for each mean  
401 EPI image in respect to the EPI brain template with the use of the specific 'object masking  
402 image' file on an individual basis. The normalization of the regular EPI images was  
403 performed by applying those normalization parameters using the sinc-interpolation  
404 method followed by a last smoothing step with a large kernel size of 15 mm. Voxel size of  
405 all normalized data was  $2 \times 2 \times 2$  mm.

### 3.3.2. SPM (statistical parametric mapping) analysis

A comprehensive SPM model including 180 first-level effects: 3 tasks (SW, NW, SNT)  $\times$  two presentation rates (slow, fast)  $\times$  2 repetitions for each condition  $\times$  16 subjects, was created. A box-car model, convoluted with the standard hemodynamic response function was used to contrast any given condition to its baseline as the first level analysis. To contrast between the two groups or between stimulus presentation rates within a task or between different tasks, a second level analysis was performed based on a paired *t*-test. All significance levels reported were corrected for multiple comparisons across the whole available brain volume unless stated otherwise and were kept at  $p < 0.05$ . In the latter cases, a small volume correction (SVC) based on the Gaussian Random Field theory was applied defined by the following ROIs: left and right peri-sylvian language area, bilateral extra-striate visual areas, bilateral cunei and pre-cunei, and are shown in Fig. 1(a).

## 4. Results

### 4.1. Background behavioral measures

Analyses of variance (ANOVAs) were conducted in order to determine group differences between the dyslexic and normal readers on each of the baseline behavioral measures. The two groups were matched on non-verbal IQ (Raven standard progressive matrices) and no significant differences between the two groups were found in reading comprehension (Table 1). Significant differences were found between the two groups on most of the other baseline measures (Table 1). Dyslexic readers were both less accurate and slower than normal readers on measures of decoding, reading time, phonological, orthographic and working memory tests. Dyslexic readers achieved lower scores on the verbal fluency measures and were slower on the WAIS digit symbols and the symbol search.

### 4.2. fMRI measures

In all three tasks, there were no significant differences in terms of performance (accuracy) between the dyslexics and the normal readers. Moreover, there were no significant reductions in performance in the fast, as compared to the corresponding slow, stimulus presentation (duration) rate conditions in any of the dyslexic participants or normal readers; both groups maintaining above 90% correct performance. The imaging data analysis, on the other hand, showed some significant differential effects of the two stimulus duration rates on reading and script decoding in the two study groups, as well as clear differences in the pattern of brain activations induced by the various tasks in the two reading groups.

A summary of the main brain imaging results (significant differential activations) for the comparison of the two study groups is presented in Table 2(a–d). Data for the three reading tasks (SW, NW and SNT) for the two-stimulus presentation rate conditions (fast and slow) as well as pooled data across all three conditions and across both presentation

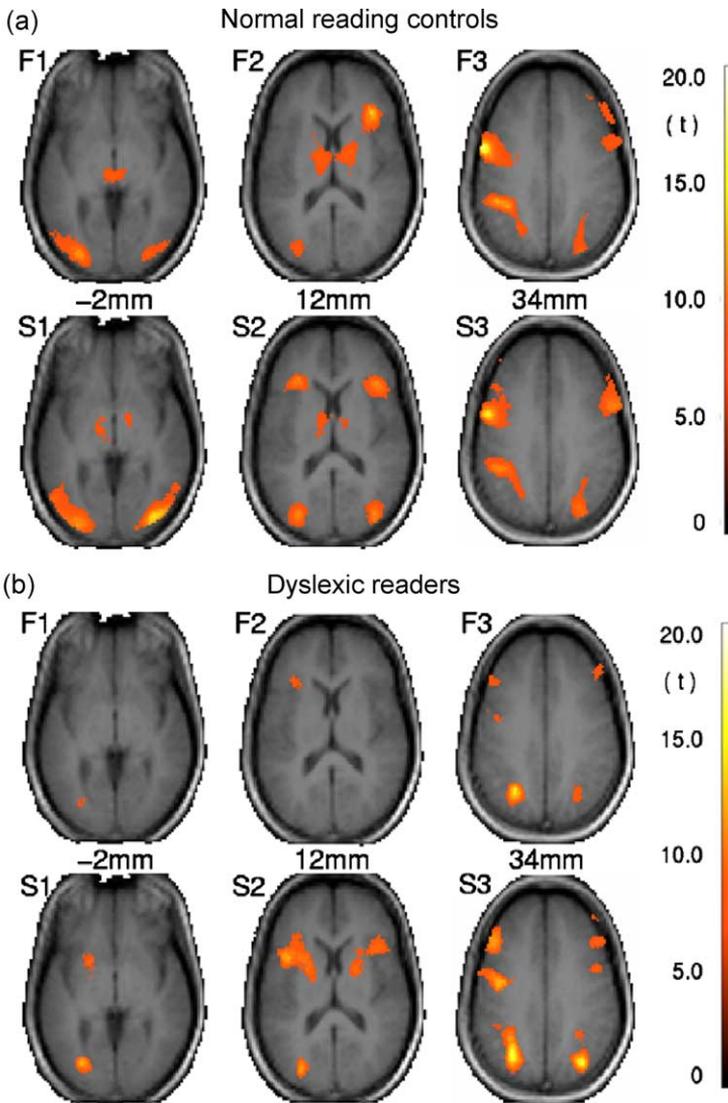


Fig. 1. Pattern of brain activations evoked in the NW task in the two reading groups: (a) normal reading controls; (b) dyslexic readers. Corresponding axial slices, oriented in the AC–PC plane are shown with their respective  $z$  coordinates (mm);  $z=0$  is the AC–PC line. F1, F2, F3—fast stimulus presentation rate ('fast' condition); S1, S2, S3—slow stimulus presentation rate ('slow' condition). There were clear activations in sub-cortical structures (the basal ganglia and thalami) as well but with no significant between group differences. The  $t$ -score threshold was at  $p < 0.05$  corrected for multiple comparisons. The color bars represent the  $t$ -score range.

rate conditions are shown. Both cluster size (number of activated voxels within a given area) and the  $t$ -score of the corresponding peak voxels are shown.

The largest differences between groups were found in the *NW task* in which participants were required to indicate whether each target pseudo-word contained or did not contain

Table 2

Brain regions demonstrating a differential response during task performance in dyslexics and normal reading controls (voxel-based group analysis)

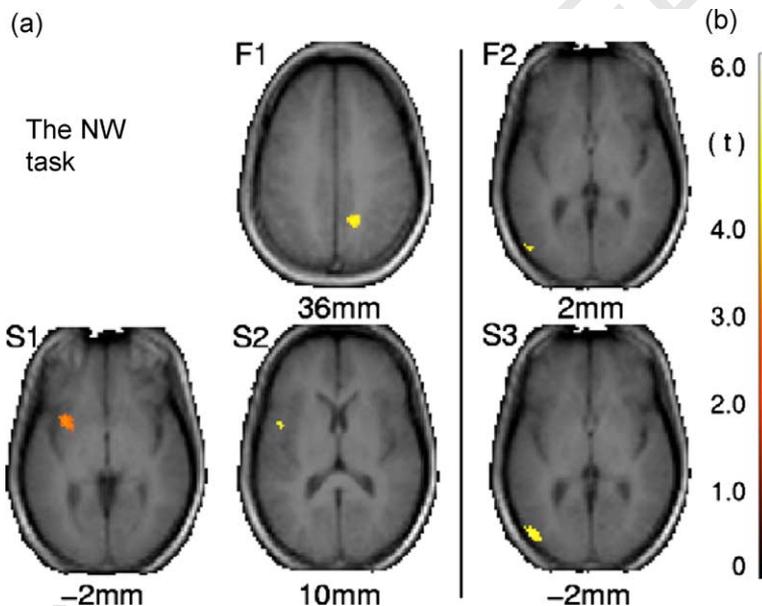
Region	Comp	Con- dition	xyz	Size	<i>t</i>	<i>p</i>	
(a) NW task							
L ant insula	d > c	Slow	−32 36 −2	127	4.08	0.0002*	
L front operculum	d > c	Slow	−44 32 10	16	4.82	0.022 (SVC)	
R pre-cuneus	d > c	Fast	14 −50 38	68	4.97	0.0067 (SVC)	
L ESVC	c > d	Fast	−46 −48 2	7	4.48	0.0307 (SVC)	
L ESVC	c > d	Slow	−46 −50 −2	208	5.14	0.0065 (SVC)	
Region	Comp	Condition	Task	xyz	Size	<i>t</i>	<i>p</i>
(b) SW task							
L ESVC	c > d	Fast	SW	−42 −52 8	118	4.68	0.0158 (SVC)
Region	Comp	Condition	Task	xyz	Size	<i>t</i>	<i>p</i>
(c) SNT task							
R temp- parietal	c > d	Fast	SNT	44 −54 0	28	4.55	0.0356 (SVC)
Region	Comp	xyz	Size	<i>t</i>	<i>p</i>		
(d) Pooled data comparison (NW + SW + SNT)							
R pre-cuneus	d > c	14 −48 34	426	4.75	0.0008 (SVC)		
L ant insula	d > c	−26 38 −6	53	4.31	0.0098 (SVC)		
L premotor	d > c	−60 32 18	461	5.83	** (SVC)		
R post insula	d > c	38 8 18	236	4.15	0.0007*		
L ESVC	c > d	−48 −48 0	1806	9.63	*** (SVC)		
R ESVC	c > d	48 −38 −6	976	7.84	*** (SVC)		
L Caudate	c > d						

Data for the two stimulus presentation rates (slow and fast) is shown: (a) SW task; (b) NW task; (c) SNT task; (d) data pooled across all three conditions (SW + NW + SNT). d > c, brain areas in which activity evoked by reading in the dyslexics significantly exceeds the activity level in the control subjects; c > d, brain areas in which activity evoked by reading in the control individuals significantly exceeded the activity level in the dyslexics. \*, uncorrected significance levels were kept at  $p < 0.001$ ; \*\* $p < 10^{-4}$ ; \*\*\* $p < 10^{-9}$ ; SVC, small volume correction for multiple comparisons. L, left hemisphere; R, right hemisphere; ESVC, extra-striate visual cortex; ant., anterior; temp-parietal, temporo-parietal; IPS, intra-parietal sulcus; MTG, middle temporal gyrus.

two similarly sounding elements (phonological judgment). Fig. 1(a) depicts the brain regions wherein significant activations (group average main effects) were evoked in the normal reading control participants, in the NW task. Both stimulus presentation rate conditions (fast and slow) activated the left pre-motor and opercular areas, to a lesser extent the right frontal operculum, the left anterior insula, and bilaterally the intra-parietal sulci (including the left dorso-anterior supramarginal gyrus). Significant bilateral

541 activation of the extra-striate cortices occurred in both presentation conditions, albeit  
 542 stronger during the fast presentation, especially on the right. The anterior insula (including  
 543 the internal frontal operculum) showed bilateral activation only for the slow presentation  
 544 condition, with activation shifting to the right in the fast stimulus presentation condition.  
 545 Fig. 1(b) depicts the group average main effects for the dyslexics in the fast and the slow  
 546 presentation rates in the NW task. As in the normal reading controls the left pre-motor, the  
 547 left anterior insula and bilaterally the intra-parietal sulci with some extension into the left  
 548 dorso-anterior supramarginal gyrus were significantly activated in the slow condition, as  
 549 well as the left extra-striate visual areas (no significant activation was found in the right  
 550 extra-striate areas) and the left more than right dorso-lateral prefrontal cortex. In the fast  
 551 condition, in addition to the parietal (regions related to the intra-parietal sulcus)  
 552 activations (left more than right) significant activations were found in the left anterior  
 553 insula and relatively less extensive activations in the dorso-lateral pre-frontal cortex and  
 554 in the left extra-striate visual areas.

555 Fig. 2 and Table 3(a) present the main results of the comparisons between groups in the  
 556 NW task. In the slow presentation rate condition, dyslexics, as compared to the normal  
 557 readers, showed significantly higher activations in the left anterior peri-sylvian regions.  
 558 The control readers, on the other hand, showed significantly more activation in the left  
 559 (occipito-temporal) extra-striate cortex. However, the most surprising result (Table 1) was  
 560 that the imposed acceleration of script decoding (the fast stimulus presentation condition)  
 561



582 Fig. 2. Brain regions in which differential responses were evoked in the NW task in the two reading groups:  
 583 (a) dyslexic > control readers; (b) control > dyslexic readers. F1, F2—fast stimulus presentation rate ('fast'  
 584 condition); S1, S2, S3—slow stimulus presentation rate ('slow' condition). Axial slice level is indicated by the z  
 585 (mm);  $z=0$  is the AC-PC line. The  $t$ -score threshold was at  $p < 0.05$  corrected for multiple comparisons. The  
 586 color bar represents the  $t$ -score range.

Table 3

Brain response pattern in the SNT task ('slow' and 'fast' conditions) in normal reading controls

Region	Slow			Fast		
	xyz	<i>t</i>	<i>p</i> (corr)	xyz	<i>t</i>	<i>p</i> (corr)
L FO	−44 30 34	12.02	0.0005			
L premotor	−46 16 44	10.7	0.002	−46 14 44	9.26	0.013
L ant ins/ IFG	−38 60 61	7.39	10 <sup>−5</sup>	−46 62 4	427	0.0003
R ant ins	32 60 6	12.73	0.0003	42 60 4	10.81	0.0035
L MTG	−58 −14 −2	15.83	10 <sup>−4</sup>	−48 −18	11.11	0.0026
L ESVC	−30 −54 −6	9.53	0.0061	−6		
				−26 −56	8.7	0.022
R ESVC	34 −50 −6	9.69	0.0052	−6		
				26 −58 −6	9.16	0.013

L, left; R, right; FO, frontal operculum; ant ins, anterior insula; IFG, inferior frontal gyrus; MTG, middle temporal gyrus; ESVC, extra-striate visual cortex. Corr., small volume correction.

resulted in only minimal differences between the brain activation patterns of the two reading proficiency groups (i.e. a relative 'normalization' of the evoked brain response patterns in the dyslexics' brains). The Rt pre-cuneus was the only brain area significantly showing stronger metabolic demands in the NW task in dyslexics vs. control readers at the fast NW task and the differential activation in the left extra-striate visual areas was reduced. Analysis of the pooled data across both the fast and the slow NW conditions revealed that the main differences between the two population groups were somewhat similar to the differences found in the slow condition (Table 2(a)): in the dyslexics the left opercular regions, as well as the right pre-cuneus, were engaged significantly more (corrected,  $p < 0.004$  and  $p < 0.0006$ , respectively) while the normal reading controls seemed to rely on their visual (extra-striate) areas (left more than right) (corrected,  $p < 0.0003$  and  $p < 0.0017$ , respectively).

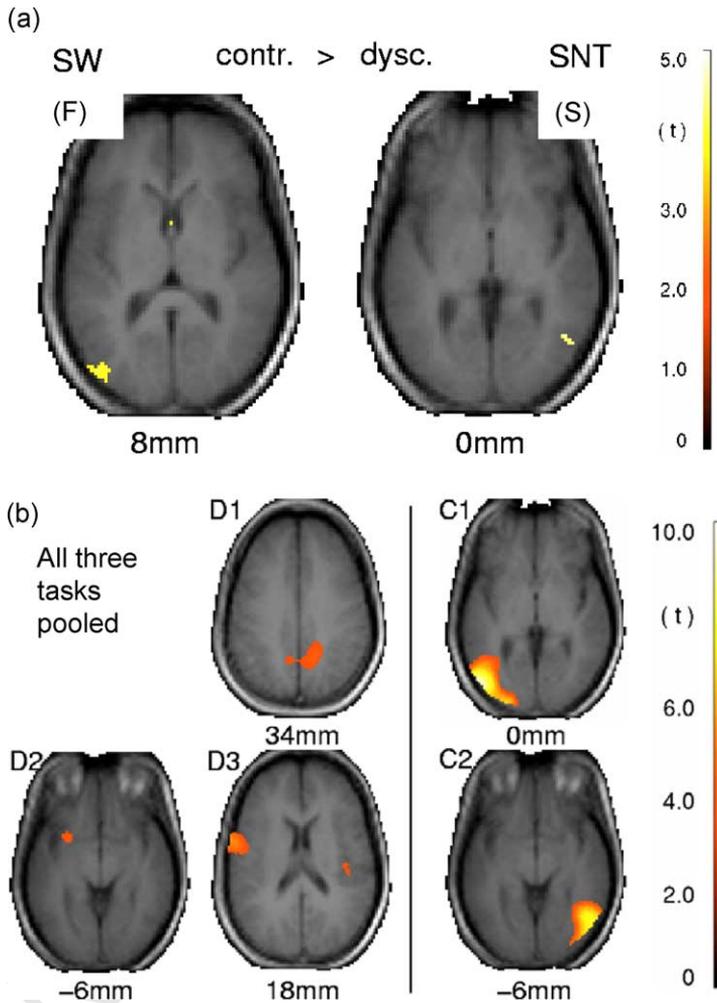
The brain activation pattern in the SNT task in the normal reading control subjects is shown in Table 3. Significant activations were found for both presentation rate conditions in the left frontal operculum and bilaterally in the anterior insula as well as the left middle temporal gyrus. Bilateral small extra-striate activation foci were detected in the slow condition, and to a lesser extent in the fast condition. Significant activation was also found in the left pre-motor area.

In the normal reading controls, a comparison between the brain response pattern evoked by SW task as compared to the NW task revealed that a right posterior parietal cortex focus (24 −48 32) was more active in the NW task (corrected,  $p < 0.005$ ). Only a very small difference in evoked response pattern was found when the SNT was compared to the SW task. This difference was in the left anterior middle temporal gyrus (−56 16 −6) (uncorrected,  $p < 0.001$ ) which activated more in the SNT task.

There were however, no significant differences in the evoked response patterns detected when the dyslexics, as a group, were compared to the normal reading controls, in either the SW and the SNT tasks, in the slow condition (Table 2(b) and (c)). The only significant differences in the brain activation patterns of the two groups, were found in the fast reading

631 conditions, with significantly more evoked activation in the left lateral extra-striate visual  
 632 regions of the normal readers, compared to the dyslexics, in the SW task, and relatively  
 633 increased activation in the posterior right temporal regions of the normal reading controls  
 634 in the SNT task (Fig. 3(a)).

635 To enhance statistical power, the data from all three tasks was pooled (NW + SW +  
 636 SNT) and the differences, between the two groups in the evoked brain activity across all  
 637



670 Fig. 3. Differential activations in dyslexic and normal reading controls. (a) Results for the SW (left panel) and the  
 671 SNT (right panel) tasks. (F) fast stimulus presentation rate ('fast' condition); (S) slow stimulus presentation rate  
 672 ('slow' condition). (b) Results for all three tasks pooled. D1, D2, D3 (left panels) depict brain regions showing  
 673 more extensive engagement in the dyslexics' brains than in the normal reading controls. C1, C2 (right panels)  
 674 depict brain regions wherein control readers had relatively higher brain activations compared to dyslexics. Axial  
 675 slice level is indicated by the  $z$  (mm);  $z=0$  is the AC-PC line. The  $t$ -score threshold was at  $p < 0.05$  corrected for  
 multiple comparisons. The color bars represent the  $t$ -score range.

676 three reading tasks, was compared in both the slow and the fast conditions (Fig. 3(b)). Due  
677 to the better statistical power (as compared to the analysis of each task by itself) the size of  
678 all activation clusters and their statistical significance were increased in the pooled data  
679 analysis. The results of the pooled data analysis (Table 2(d)) were consistent with the  
680 results of the analysis of the NW task. While the normal reading controls had significantly  
681 higher engagement (compared to the dyslexics) of the ventro-lateral extra-striate cortices  
682 (with a left hemisphere advantage), there were significantly higher activations, across all  
683 reading and script decoding tasks, in the left inferior frontal gyrus and the left parietal  
684 operculum as well as the Rt pre-cuneus. Thus, the pooled results indicate a larger reliance  
685 on left peri-sylvian regions in the dyslexics as compared to the normal reading controls.  
686  
687

## 688 5. Discussion

689

690 The current study was designed to explore the possibility that time-constrained reading  
691 (acceleration) may enhance reading effectiveness among dyslexic readers by prompting  
692 the dyslexic brain to process graphemic information in a manner different from the one  
693 engaged routinely (i.e. with no time constraints imposed) in reading. Altogether the results  
694 of this preliminary study of a small group of adult dyslexics suggest that for some reading  
695 tasks (semantic judgment of single words (SW) and sentence plausibility judgment (SNT))  
696 increasing temporal constraints in script presentation may result in an uncovering of the  
697 differences between the brain responses evoked in adult dyslexics and normal reading  
698 adults but also in significant changes in the engagement of different brain regions in task  
699 performance. However, our results also show that in a non-lexical reading (script  
700 decoding) task (the NW task) the large differences in the evoked brain activity patterns in  
701 the two groups may have decreased with the increasing of the reading rate. This somewhat  
702 surprising finding is in line with the notion previously suggested in the context of the  
703 acceleration phenomenon. The fMRI BOLD imaging results thus clearly complement the  
704 previously reported findings from ERP studies wherein the effects of varying stimulus  
705 presentation rates were studied (Breznitz et al., 1993; Breznitz & Leiken, 2000; Leiken &  
706 Breznitz, 2001). These studies have shown that in both normal reading and dyslexic  
707 individuals ERP latencies (P200 and P300) appeared earlier in the fast as compared to the  
708 slow stimulus presentation conditions. However, latency differences between the two  
709 presentation conditions were more pronounced in the dyslexic individuals, thus indicating  
710 that the dyslexics may come nearer to closing the gap, relative to normal reading control,  
711 in processing speed during the faster word presentation rates. Moreover, the spatial  
712 distribution (electrode) of the maxima of the ERP components were changed as a function  
713 of acceleration in both groups, suggesting that a qualitative shift in processing may also  
714 occur with accelerated stimulus presentation.

715 As a recent review (see Zeffiro and Eden (2000)) has pointed out, there has been  
716 continuous interest in the notion that neural systems, specifically those involved in  
717 phonological processing and phonological memory, can be strongly modulated by  
718 stimulus presentation and task performance rates. The demonstration that visual cortex  
719 activation was stimulus presentation rate dependent (Fox & Raichle, 1984) was extended  
720 in two landmark studies (Price et al., 1992, 1994) on listening to words and oral reading

721 that showed that the engagement of frontal, temporal and parietal cortical areas, including  
722 those outside the primary and secondary sensory processing areas, may be stimulus  
723 duration dependent in quite a non-linear manner. Moreover, the stimulus presentation–  
724 duration dependent differences in brain areas engaged by task performance were not  
725 linearly related to performance (which was at ceiling). These findings may be related to the  
726 notion that time constraints on stimuli (visual or auditory) may cause a large differential  
727 response in dyslexics as compared to normal readers, because of a specific dysfunction in  
728 the magnocellular system (for review, see Zeffiro and Eden (2000)).

729 In the SW and SNT tasks, the only significant differences between the dyslexic readers  
730 and the normal reading controls (between groups comparison) in brain engaged in task  
731 performance were found in the fast condition with significantly more activation in the Lt  
732 extra-striate cortex of the normal readers, compared to the dyslexics, in the SW task and  
733 relatively increased engagement of the Rt temporo-parietal cortex in the SNT task. These  
734 findings are consistent with a number of studies (mainly of English) showing reliance on  
735 visual processing areas in phonological decision tasks (Paulesu et al., 1996; Pugh et al.,  
736 1996; Rumsey et al., 1997b; Shaywitz et al., 1998, in Zeffiro and Eden (2000)) and in  
737 reading (Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995; Price, Wise, &  
738 Frackowiak, 1996). In the rhyme detection task as well as in word recognition, Rumsey  
739 et al. (1992, 1997c) found that (along with other differences) the right inferior parietal  
740 regions exhibited regional cerebral blood flow increases in the normal readers compared to  
741 dyslexics. Moreover, it has been suggested that right parietal cortex engagement may  
742 decrease with increased experience in reading different scripts (Chee, Hon, Lee, & Soon,  
743 2001). Novel word forms as in mirror reading (Poldrack, Desmond, Glover, & Gabrieli,  
744 1998) and in reading a less well-experienced alphabet (Chen, Fu, Iversen, Smith, &  
745 Mathews, 2001) were also reported to correlate with higher right parietal activations.  
746 These activations decreased with increasing familiarity with the novel scripts. Never-  
747 theless, while the general trend for the differences between the two study populations is in  
748 line with results obtained in previous studies (with languages other than Hebrew) the  
749 comparison in the slow conditions failed to show any significant differences. One cannot  
750 rule out that this negative finding may be the result of insufficient statistical power (indeed  
751 the largest differences were found in the analysis of the pooled data). However, the finding  
752 of no difference between the two reading groups in the two reading tasks, SW and SNT  
753 wherein quite common lexical items were presented, may relate, in part, to the fact that the  
754 dyslexics were highly functioning adults who were all competent enough to study at  
755 university level. There are several studies showing that deficits in phonological processing  
756 are pervasive and persistent problems even in ‘high functioning’ adult dyslexics (Bruck,  
757 1990, 1998). However, the most pronounced deficit in this group may be dysfluency  
758 (Levy, 2001; Meyer & Felton, 1999) i.e. the amount of text that can be read at a given time  
759 interval even by these high functioning individuals is very limited (Bruck, 1990, 1998;  
760 Brunswick, McCrory, Price, Frith, & Frith, 1999; Leong, 1999; Lovett et al., 1994).

761 The largest differences between the two reading groups were found in the *NW task* in  
762 which participants were required to indicate whether each target pseudo-word contained or  
763 did not contain two similarly sounding elements (phonological judgment). This task was  
764 unique in that for both participant groups, dyslexics and normal readers, the items  
765 presented were presumably novel and non-lexical to a similar degree. Thus, the effects of

766 differential exposure (i.e. accumulating differential experience with lexical items) (Bitan  
767 & Karni, 2003; Ofen-Noy et al., 2003) were at minimum. In the slow presentation rate  
768 condition, dyslexics, as compared to the normal readers, showed significantly higher  
769 activations in the left inferior frontal regions (BA 44/6) including the frontal operculum.  
770 The control readers, on the other hand, showed significantly more activation in the left  
771 extra-striate cortex. However, the most surprising result—in line with our working  
772 hypothesis—was that the acceleration of reading (i.e. the same task performed at the fast  
773 rate) resulted in a relative normalization of the brain area engagement patterns in the  
774 dyslexic readers. It is reasonable to assume that at least in part this minimalization of the  
775 differences between the two reading groups was due to increased left frontal engagement  
776 in the normal readers group in the fast condition (Fig. 1(a)) in line with the results in the  
777 SNT task (Table 3). This interpretation is in line with the notion of presentation rate  
778 dependent shifts in activation patterns in normal reading individuals (Price et al., 1994)  
779 and also with the notion that in conditions wherein the reading tasks are more demanding  
780 (Chee et al., 2001; Clark & Wagner, 2003) the left inferior frontal cortex activation may  
781 increase. Nevertheless, the results from the rather phonologically demanding, and equally  
782 novel (to the two reading groups) NW task show that the differences between the evoked  
783 patterns of activation in dyslexics' and control reader's brains may decrease with time-  
784 constrained script decoding, i.e. with the forced increase of the reading rate. Moreover, the  
785 results of the first level analysis (Fig. 1) suggest that this normalization may also be due to  
786 a marked shift, in the dyslexics, in the relative engagement of different brain areas in task  
787 performance when stimulus presentation rates were increased.

788 Altogether, the results from the pooled data analysis (NW + SW + SNT) are consistent  
789 with the NW results in the slow condition. The results suggest that the dyslexics may rely  
790 more on the left peri-sylvian structures (i.e. canonical language areas) like Broca's area  
791 and the parietal operculum as well as the Rt pre-cuneus, while control readers made  
792 significantly more use of their extra-striate cortices (with a left hemisphere advantage).

793 The Hebrew dyslexics' left inferior frontal gyrus over-engagement in the NW task is in  
794 line with the findings in other languages (Paulesu et al., 1996; Shaywitz et al., 1997). There  
795 is a very large body of evidence linking the left inferior prefrontal cortex to phonological  
796 processes, and specifically this area's involvement in tasks requiring grapheme to  
797 phoneme translation (Chen et al., 2001; Clark & Wagner, 2003; Demonet et al., 1992;  
798 Fiebach, Friederici, Muller, & Von Cramon, 2002). There is also evidence that as reading  
799 becomes more proficient (and presumably more word form dependent) the involvement of  
800 left inferior frontal areas decreases (Clark & Wagner, 2003; Shaywitz et al., 1997). In a  
801 recent study, Chee et al. (2001) tested the effects of proficiency versus alphabetality in  
802 Chinese–English bilinguals and found that reading in the less proficient language activated  
803 the left inferior prefrontal area as well as the bilateral parietal regions regardless of the  
804 specific language and irrespective of whether alphabetical decoding was possible. There is  
805 also some empirical support for the notion that the left inferior prefrontal cortex may be  
806 involved in the generation of rule-like behavior (Clark & Wagner, 2003; Tettamanti et al.,  
807 2002). Pooling the data of the fast and slow NW conditions showed that the main  
808 differences between the two population groups were as follows: dyslexics activated  
809 relatively more the left inferior frontal language area and the parietal operculum as well as  
810 the right pre-cuneus, while the normal reading controls seemed to rely on their visual

811 (extra-striate) areas (left more than right). The extra-striate cortical areas have been  
812 implicated in proficient reading and phonological processing although these areas may  
813 also be related to orthographic processing (Clark & Wagner, 2003; Price et al., 1996;  
814 Rumsey et al., 1997a; Shaywitz et al., 1997).

815 Although the cuneus and pre-cuneus (bilaterally) were found to be over activated in  
816 previous studies comparing dyslexics to normal readers (Rumsey et al., 1997a), the current  
817 study design does not afford a clear explanation of the finding that the right pre-cuneus was  
818 the only brain area significantly showing stronger metabolic demand in the NW task in  
819 dyslexics vs. control readers in the fast task condition. It is of interest that, using a task  
820 quite similar to the NW task, the cuneus and pre-cuneus were shown to be more active  
821 metabolically in a recent study comparing phonological processing of English to 'Foreign'  
822 items (Clark & Wagner, 2003). The left lateral pre-motor areas showed significantly larger  
823 activation in the slow condition of the SNT and in the NW tasks in the normal readers (as  
824 well as in the dyslexics). As motor responses were made only during the stimulus  
825 presentation intervals (task performance epochs, blocks) the lateral pre-motor areas (the  
826 primary motor cortex hand area was not included in the scanned volume) may in part at  
827 least, be ascribed to the generation of motor responses. However, there are several  
828 indications that the lateral pre-motor areas, specifically the more ventral parts may be  
829 involved in various reading and phonological judgment tasks as well as verbal memory  
830 (Clark & Wagner, 2003; Paulesu et al., 1996; Rumsey et al., 1997b). The finding that these  
831 areas were specifically activated more in the slow condition in the SNT and NW task  
832 (given that the nature of the motor responses and their rates in the task activation epochs,  
833 were similar in all three tasks and stimulus presentation rate conditions) lends indirect  
834 support to the notion that this increased activation of left pre-motor areas was indeed task  
835 dependent. Thus, the relatively larger reliance on pre-motor areas in normal readers during  
836 slow sentence reading may indicate that the task demands were resolved through a  
837 stronger reliance on phonological processing, but less so in the time-constrained fast  
838 condition.

839 Hebrew has a shallow orthography and a characteristic (Semitic languages)  
840 morphology and may pose for the reader some unique problems compared to those  
841 encountered in English and related languages (Frost, 1994). The many points of similarity  
842 between the current findings and the large literature on English dyslexics support,  
843 however, the notion that the over reliance on Lt-IFG and the failure to evolve effective  
844 extra-striate processing routines may not be language specific. This proposal is in line with  
845 the notion of proficiency and familiarity with script systems as an important parameter in  
846 determining the pattern of brain activation in reading and script decoding (Bitan & Karni,  
847 2003; Chee et al., 2001; Clark & Wagner, 2003; Price et al., 1996).

848 Altogether, our results show that: (a) no differences were found between the brain  
849 activation patterns evoked in the dyslexics and the normal reading controls in either the  
850 SW or the SNT task in the slow stimulus presentation condition. However, the normal  
851 reading controls had relatively larger evoked responses in (the mainly left) extra-striate  
852 visual areas when stimulus presentation times were shortened in the SW task. (b) The  
853 largest differences in the brain activation patterns, between the dyslexic readers and  
854 the normal reading controls, were evoked in the NW task. However, the differences  
855 between the two groups became smaller as the stimulus presentation durations were

856 decreased, i.e. when reading and script decoding were performed with increasing time  
 857 constraints (more differences in brain response patterns in the slow than in the fast  
 858 conditions). (c) There were significantly higher activations, across all reading and script  
 859 decoding tasks (pooled data), in the left inferior frontal gyrus (LIPC including Broca's  
 860 area) and the left parietal operculum as well as the right pre-cuneus in the dyslexics. While  
 861 the normal reading controls had significantly higher activations (compared to the  
 862 dyslexics) in extra-striate cortices (with a left hemisphere advantage).

863 Our results suggest that a manner of script processing much closer to the one employed  
 864 by normal reading controls may be invoked, in well compensated adult dyslexics, given  
 865 time constraints. Going somewhat beyond the data, these preliminary findings provide an  
 866 indirect indication that the differences in processing scripts between dyslexics and normal  
 867 reading adults may decrease with the increasing of the reading rate opening a way for a  
 868 possible remedial approach—reading acceleration training for dyslexics. On a more  
 869 general level our results raise the possibility, which can be empirically tested, that at least  
 870 some of the reported differences in the patterns of brain responses ascribed to  
 871 developmental, experiential factors and script system characteristics per se, and similarly  
 872 at least part of the discrepancies between different study results may be related to different  
 873 reading rates, and suggest that word presentation rates should be considered as important  
 874 parameters in determining the manner in which otherwise similar tasks are processed in  
 875 both dyslexic and normal readers.

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