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The eye movements of dyslexic children during reading and visual search: Impact of the visual attention span

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Abstract

The eye movements of 14 French dyslexic children having a VA span reduction and 14 normal readers were compared in two tasks of visual search and text reading. The dyslexic participants made a higher number of rightward fixations in reading only. They simultaneously processed the same low number of letters in both tasks whereas normal readers processed far more letters in reading. Importantly, the children's VA span abilities related to the number of letters simultaneously processed in reading. The atypical eye movements of some dyslexic readers in reading thus appear to reflect difficulties to increase their VA span according to the task request.

Keywords: Children; Dyslexia; Eye movements; Visual attention span; Text reading

1. Introduction

A huge amount of data has shown that eye movements are abnormal in dyslexia. Dyslexic individuals exhibit longer duration of fixations, shorter saccades and thus more fixations in reading than normally developing readers of the same chronological age. Such eye movement disorders have been reported in different languages, irrespective of their degree of transparency (Hutzler & Wimmer, 2004). They have been found not only in text reading but also when reading sentences (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hutzler & Wimmer, 2004; Zoccolotti et al., 1999) or single items, words or pseudo-words (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Hutzler & Wimmer, 2004; MacKeben et al., 2004). While such atypical eye movements have been implicated as the reason for the dyslexics reading difficulties (e.g., Pavlidis, 1981), other data rather suggest that the reading impairment itself leads to abnormal eye movements. The source of such atypical eye movements in dyslexia is still hotly debated, in particular their potential visual origin. Our purpose will be here to show evidence for a visual attention span dysfunction as a potential source of eye movement disorders in developmental dyslexia.

To explore whether the alteration in eye movements in dyslexic individuals results from an oculomotor disorder, most studies used simple non-verbal tasks in order to remove the effects due to the linguistic components inherent in reading. No consensus emerged from these studies. Indeed, the dyslexics' eye movements were found to show inaccurate saccades (Eden, Stein, Wood, & Wood, 1994; *but see* Biscaldi, Gezeck, & Stuhr, 1998; Crawford & Higham, 2001; Leisman & Schwartz, 1978; MacKeben et al. 2004; Trauzettel-Klosinski et al., 2002), saccadic intrusions during smooth pursuit (Adler-Grinberg & Stark, 1978; Black, Collins, De Roach, & Zubrick, 1984; Eden et al., 1994), binocular instability (see Stein, Richardson, & Fowler, 2000; *but see* De Luca et al., 1999; Lennerstrand, Ygge, & Rydberg, 1994; MacKeben et al., 2004; Trauzettel-Klosinski et al., 2002) or abnormal saccadic latencies (Bednarek, Tarnowski, & Grabowska, 2006; Biscaldi, Fisher, & Aiple, 1994; Biscaldi, Fischer, & Hartnegg,

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2000; Biscaldi et al., 1998; Dossetor & Papaioannou, 1975; Fischer, Biscaldi, & Otto, 1993; Fischer & Weber, 1990; Pirozzolo, 1979; *but see* Adler-Grinberg & Stark, 1978; Crawford & Higham, 2001) in some studies but not all. Differences in the paradigms employed could account for these contradictory results as well as differences in the dyslexics' selection criteria. Indeed in most studies, the dyslexic participants were selected on broad criteria without taking into account the heterogeneity of the dyslexic population. However, atypical eye movements might well characterize only a subset of the dyslexic children; they might also reflect different underlying dysfunctions in different types of dyslexia.

Moreover, the use of simple non-verbal tasks raises a number of questions: when evidence for oculomotor disorders comes from tasks of indirect relevance for reading (i.e., which differ grossly from the reading situation), one can question how the observed eye movement differences would influence reading. Reversely, when no oculomotor disorder is found on such tasks, one cannot rule out the possibility that some more subtle oculomotor processes are involved in reading which might be impaired in dyslexic individuals. To more specifically evaluate the oculomotor processes relevant for reading, some studies used non-verbal tasks of sequential tracking. Sequential tracking is a very simple oculomotor task which requires eye movements' sequential shifting from one non-verbal target to the other. Pavlidis (1981) and Biscaldi et al. (1998) reported atypical eye movements in dyslexic readers as compared to controls on such tasks. However, here again, most attempts to replicate these findings were unsuccessful (Black et al., 1984; Brown et al., 1983; De Luca et al., 1999; Olson, Kliegl, & Davidson, 1983a,1983b; Stanley, Smith, & Howell, 1983). In the study by De Luca et al. (1999), the eye movements of surface dyslexic participants were recorded in both sequential tracking and text reading. Results did not reveal any differences in the eye movement patterns of the dyslexic and control readers in sequential tracking but differences were indeed found in reading. In sum, there is little convincing evidence that people with dyslexia exhibit qualitatively distinct eye movement patterns in a sequential tracking task even when exhibiting atypical eye movements in reading.

However, even if the oculomotor demand of the tracking task matches some aspects of the oculomotor control required for reading, the two tasks nevertheless strongly differ. In particular, tracking does not require identification of symbols to the contrary of reading. Tasks of more immediate relevance for reading were used in other studies. Trauzettel-Klosinski et al. (2002) recorded the eye movement patterns of dyslexic and control readers during a task of pictogram naming where pictograms were grouped and arranged in paragraphs of several lines for the oculomotor and perceptual demands of the task to be functionally equivalent to those required for reading. They reported a similar number of rightward saccades for the dyslexics and the controls. Only leftward saccades occurred more frequently in dyslexics but there was a large overlap between the groups suggesting that the chance of a primary oculomotor deficit in dyslexic children was rather unlikely.

The non-reading task used by Hutzler et al. (2006) was considered to be still closer to the perceptual and oculomotor demands of reading. In this study, the dyslexic and control participants had to read aloud series of pseudo-words (e.g., GUFT). Their eye movement patterns on this task were compared to those recorded in a string processing task where they had to search through lists of consonant strings (e.g., GDRK, LBQD) for items with two adjacent identical letters (e.g., VPLL). The consonant strings were built from the pseudo-words by replacing vowels by consonants. The spatial arrangement of pseudo-words and consonant strings was the same. Hutzler et al. (2006) showed that the eye movement patterns of dyslexic and control readers did not differ when performing the visual search task, whereas they strongly differed in the reading task. Such findings were interpreted as evidence against the hypothesis of visual perceptual or oculomotor problems in developmental dyslexia. The overall findings suggest that the divergent eye movement patterns of dyslexic readers in reading primarily reflect their difficulties in successfully identifying words (for converging evidence see Hyona & Olson, 1995; Olson, Kliegl, & Davidson, 1983a). Accordingly, the source of the problems experienced by dyslexic readers is not supposed to be at the level of oculomotor control or visual processing but presumably at a higher psycholinguistic level of processing (Hutzler et al., 2006).

However, several findings suggest that, apart from the visuo-perceptual mechanisms, some visual attentional processes are involved in reading that, when impaired, could partly account for the atypical eye movements of dyslexic children. In their connectionist multitrace model of polysyllabic word reading, Ans, Carbonnel, and Valdois (1998) postulate the existence of a visual attentional (VA) window through which information is extracted from the input letter string. The size of the VA window determines whether processing will be done in global or in analytic mode. A large window extending over the whole input letter-string allows reading in global mode whereas the VA window size is reduced to parts of the input sequence in analytic processing. The visual attention span (''VA span'' hereafter), was defined as the number of distinct visual elements which can be processed in parallel in a multi-element array, by reference to the ''VA window'' as theoretically defined in the multitrace model (Bosse, Tainturier, & Valdois, 2007). Valdois et al. (2003) and Bosse et al. (2007) showed that some dyslexic children have a VA span disorder characterised by a reduction in the number of letters which can be processed in parallel. At the oculomotor level, such a disorder should result in shorter saccades, thus a higher number of rightward fixations, in the dyslexic than control participants when reading.

In line with this prediction, Hawelka and Wimmer (2005) showed that dyslexic children exhibited lower performance on the longer arrays of a multi-element processing task and a substantial correlation was reported between their number of eye movements in single word and pseudo-word reading and their ability to process multi-element arrays. Such findings are compatible with the hypothesis of a relationship between the size of the VA span and the number of eye movements in reading. However in their study, number of eye movements was considered as a whole without specifying whether the relation held for rightward as well as leftward saccades. Moreover, the Hawelka and Wimmer's (2005) hypothesis that impaired visual processing of multi-element arrays is associated with increasing number of eye movements should predict similar results in text reading and in those non-reading tasks which pose similar demands on the visual and oculomotor system, as for instance in Hutzler et al. (2006).

In contrast, the multitrace memory model (Ans et al., 1998) postulates that the size of the VA window (thus, the VA span in humans) varies according to the material to be processed. The VA window is reduced when processing unfamiliar items so that a smaller VA span is involved when processing pseudo-words as compared to real words in skilled readers (Valdois et al., 2006). It follows that if the size of the VA span varies according to the task in normal readers and if some dyslexic children suffer from a reduction of the VA span, then a VA span deficit might differentially affect performance in reading and visual search, even if the visual perceptual characteristics of the tasks are very similar. More specifically, if reading familiar words involves a larger VA span than performing a visual search on unfamiliar letter strings as expected within the multitrace memory framework, then a VA span reduction should more severely impact performance in reading than in visual search.

To assess this hypothesis, the eye movements of dyslexic and non-dyslexic readers were here recorded in a text reading task and in a visual search task of immediate relevance for reading. The study was undertaken on a homogeneous subgroup of dyslexic children showing a VA span disorder in the absence of phoneme awareness problems. Following the theoretical framework of reference, the number of rightward fixations in text reading was expected to be higher in the dyslexic than control children, thus revealing that a few letters were simultaneously processed at each fixation. Moreover, the VA span as measured off-line was expected to correlate with the number of rightward (but not leftward) fixations in reading. Differences in eye movements between the dyslexic and control readers were further expected to be smaller, or even to vanish, in visual search if control readers narrowed their VA span in visual search.

2. Methods

2.1. Participants

Fourteen dyslexic (11 boys; mean age = 11 years 1 month; *SD* = 12 months) and 14 control readers (9 boys; mean age = 10 years 8 months; *SD* = 7 months) participated in this study. All 28 children had French as their mother tongue. They attended school regularly, and had normal or corrected to normal vision. The two groups' mean non-verbal IQs[1] were within the normal range, and did not significantly differ (see Table 1). All the participants were free from any history of neurological or psychiatric illness, or any medical treatment. All subjects and their parents gave informed written consent prior to participating. All the participants were selected from an initial larger pool of children who underwent clinical examination before the experiment to evaluate their reading skills together with their phonological and visual attentional processing skills.

Table 1
Means and standard deviations of the dyslexic and control group for the defining and descriptive measures

	Dyslexics ($n = 14$) M (*SD*)	Normal-readers ($n = 14$) M (*SD*)	$F(1,26)$
Age (months)	133.5 (12.1)	128 (7.4)	2.10
Non-verbal intelligence (percentile)	48.8 (22.59)	62.5 (31.8)	1.71
Reading age (months)	87.8 (6.9)	125.5 (7.7)	186.52***
VA span (/5)	3.2 (0.44)	4.5 (0.31)	80.18***
Global report (/5)	2.98 (0.42)	4.45 (0.41)	87.69***
Z-score	−2.27 (0.68)	0.52 (0.8)	
Partial report (/5)	3.40 (0.7)	4.51 (0.32)	29.16***
Z-score	−1.76 (1.48)	0.37 (0.71)	
Phonological score (/15)	10.4 (2.2)	9.86 (3.4)	0.25
Phoneme segmentation (/15)	10.73 (3.14)	8.36 (3.48)	3.60*
Z-score	0.74 (0.81)	0.13 (0.85)	
Phoneme deletion (/10)	6.71 (1.73)	7.57 (2.47)	1.13
Z-score	0.15 (0.69)	0.42 (0.99)	

* $p < .05$.
*** $p < .001$.

2.2. Neuropsychological assessment

2.2.1. Reading skills

The diagnosis of developmental dyslexia was established using both inventory and testing procedures in accordance with the guidelines of the ICD-10 Classification of Mental and Behavioral Disorders. The "Alouette Reading Test" (Lefavrais, 1965) was used to estimate the reading age of each child. The children who performed poorly on the Alouette reading test were further asked to read aloud two lists of 20 irregular words of high and low frequency and two lists of 20 matched pseudo-words (taken from the ODEDYS test, Jacquier-Roux, Valdois, & Zorman, 2002). The participants were diagnosed as dyslexic if their reading age was at least 24 months lower than expected according to their chronological age and if they scored at least 1.65 standard deviations below the average on tests of irregular word and/or pseudo-word reading (on either speed or accuracy) whereas their IQ was within the normal range. In the control group, the children's reading age was no more than 12 months higher or lower than expected according to their chronological age; their performance was on the average in both irregular word and pseudo-word reading.

2.2.2. Phoneme awareness

Phoneme awareness was evaluated by means of a phoneme deletion task performed on pseudo-words (e.g., /drij/-/j/→/dri/), and a phoneme segmentation task (e.g., "four" →/f/-/u/-/R/). A phonological score was calculated by normalizing and averaging the two metaphonological scores.

[1] The Raven matrices (PM38; Raven, 1940) were used for the assessment of non-verbal intelligence.

2.2.3. Visual attention span

The participants were assessed using two tasks of global and partial letter-report designed to estimate the number of distinct letters that could be extracted in parallel from a brief visual display (taken from Bosse et al., 2007). The tasks required the report of a single letter or of all of the letters of briefly presented consonant strings.

2.2.3.1. Stimuli. Random 5-letter strings (e.g., R H S D M) were built up from 10 consonants (B, P, T, F, L, M, D, S, R, H). The letters were presented in upper-case (Geneva, 0.8° high) in black on a white background. The strings contained no repeated letters. The distance between adjacent letters was of 0.57° in order to avoid lateral masking. The whole line subtended an angle of approximately 5.4°.

Twenty 5-letter strings were successively presented in global report; each letter was used 10 times (twice in each position). Fifty random 5-letter strings were presented in partial report. Each letter occurred 25 times and each appeared five times in each position.

2.2.3.2. Procedure. At the start of each trial, a central fixation point was presented for 1000 ms followed by a blank screen for 50 ms. A letter string was then presented at the centre of the display for 200 ms, a duration which corresponds to the mean duration of fixations in reading, long enough for an extended glimpse, yet too short for a useful eye movement. In global report, the participants' task was to report verbally all the letters immediately after they disappeared. In partial report, a probe—a vertical bar—indicating the letter to be reported was presented for 50 ms, 1.1° below the target letter, at the offset of the letter string. Each letter was used as target once in each position. Participants were asked to report the cued letter only. In both tasks, the experimenter pressed a button to start the next trial after the participant's oral response. Eye movements were not monitored, but the requirement of central fixation was strongly emphasized and repeated at regular intervals during the experiment. The experimental trials were preceded by 10 training trials for which participants received feedback. The dependent measures were the mean number of letters accurately reported (identity not location) across the 20 trials (Max = 5) or across the 50 trials multiplied by the number of displayed letters (Max = 5) in the global and partial report tasks, respectively. The VA span was estimated as the mean of these two measures (Max = 5).

2.3. Inclusion criteria

Only those dyslexic children who had a VA span deficit (global and partial report scores below the average and at least one score lower than the 10th percentile of children of the same age) were included in the experimental group. None of the normal-readers suffered from such a disorder. Table 1 gives the means and standard deviations of the dyslexic and control readers on the descriptive and defining measures and the *F*-values for the group comparisons.[2]

A significant difference of 45 months (SD = 12 months) between chronological age and reading age characterises the dyslexic group ($F(1,26) = 308.42$; $p < .001$), whereas reading age does not differ significantly from chronological age in normal readers (mean difference = 2 months; SD = 6 months; $F < 1$). Reading performance of the dyslexic participants was compared to norms built up from 130 3rd grade children with various socio-cultural backgrounds (taken from Bosse & Valdois, 2007). The dyslexic participants showed a word identification deficit mainly characterised by an excessive slowness in both irregular word and pseudo-word reading. Their mean reading rates were 142 ms ($SD = 82$; Z-score = 5.47; $SD = 4.5$) and 114 ms ($SD = 46$; Z-score = 3.58; $SD = 2.53$) on average for the irregular words and pseudo-words, respectively. The reading rate disorder was stronger for irregular words than for pseudo-words (Z-scores = 5.47 vs. 3.58; $F(1,26) = 7.71$; $p < .05$). Moreover, the dyslexic participants' reading accuracy performance was more than two standard deviations below that of control readers for the irregular words only, with a mean performance of 19.1 ($SD = 7.0$; Z-score = −2.80; $SD = 1.61$) versus 28.7 ($SD = 6.3$; Z-score = −1.27; $SD = 1.55$) for the pseudo-words. Hence, the reading profile of the dyslexic group fits well with the surface dyslexia reading profile as typically described. The dyslexic and normal readers performed similarly on the phoneme awareness tasks ($F < 1$). However as compared to controls, the dyslexic participants exhibited a VA span disorder ($F(1,26) = 80.18$; $p < .001$) characterised by an impaired performance in both global and partial report ($F(1,26) = 87.69$; $p < .001$ and $F(1, 26) = 29.16$; $p < .001$, respectively). Overall, the dyslexic group exhibits a VA span disorder in the absence of phoneme awareness problems.

[2] The phoneme deletion and phoneme segmentation scores correlate (Pearson's correlation coefficient $r = .42$; $p < .05$), which justifies the computation of a composite phonological score. In the same way, global report and partial report scores correlate (Pearson's correlation coefficient $r = .72$; $p < .01$), so that a composite VA score was computed as en estimation of the participants' VA span.

3. Experimental paradigm

3.1. Eye movement recordings

The participants' eye movements were recorded during the reading of a text passage and during a visual search task of immediate relevance for reading. Task order was counterbalanced so that half the participants in each group began with the reading task.

3.1.1. Apparatus and procedure

Eye movements were recorded from both eyes every 4 ms using a video-based EYELINK I system (SR Research) in a natural binocular viewing situation. Displays were generated using an ELSA GLADIAC MX card and a DELL P1110 monitor. Data of the right eye were used for the analysis. The Eyelink system detected eye movements as saccades when peak velocities were higher than 30°/s, when acceleration was superior to $9500°/s^2$ and when a motion higher than 0.15° occurred from the position of fixation before the saccade onset. The participants sat on a chair, 60 cm from the computer screen; Children's head was kept up at the level of the temples so that the lower jaw remained free to do the movements required for articulation. The participants were requested to stay as still as possible and to try not to blink or move their head during the recording period. The remaining small head movements when occurring were compensated by the system.

A calibration procedure was carried out before the task. The participants were required to track the position of a dot presented at nine different locations on the computer screen.

3.1.2. Stimulus material

3.1.2.1. Reading task. The stimulus used for the reading task was a paragraph of four lines, taken from a book for children.[3] As shown in Fig. 1, the paragraph contained 39 words and was fully displayed on the screen without time limit. The text was 31° wide and 6.8° high. Each letter

[3] Title of the book: "Le monstre poilu" written by H. Bichonnier, illustrated by PEF, Gallimard Editor.

Le monstre poilu vivait dans une caverne humide et grise, au milieu d'une
sombre forêt. Il avait une grosse tête posee directement sur deux pieds
ridicules, ce qui l'empêchait de courir. Il ne pouvait donc pas quitter sa
caverne.

Fig. 1. Passage used for eye movement recordings in reading aloud.

Lc mcnstrc pclln vlvslt dsns nnc csvcmc hnrctdc ct grlsc, sn mlllcn d'nnc
scmbnc fcrct. Ll svslt nnc grcssc tctc pcscc dlrctccmcnt snr dcnx plcds
nldlcnlcs, cc qnl l'cmprctsht dc ccncts. Ll nc pcnvslt dcnc pss qnlttcr ss
csvcmc.

Fig. 2. Text-like stimulus used for eye movement recordings in visual search.

subtended 0.6° of visual angle at a distance of 60 cm. The distance between the lines was 1.5°.

The participants were asked to read the text aloud. A drift correction was performed before the task; the target used to perform the drift correction was located at the beginning of the paragraph, where the first word subsequently appeared.

3.1.2.2. Visual search task. For the visual and oculomotor demands of the visual search task to be as close as possible to those required for reading, visual search was done on the text used in reading but in which vowels were replaced by consonants (see Fig. 2). As in reading, the three first lines counted 59 letters and the fourth 6 letters. The visual search task required the participants to count the number of 'R's occurring in the four lines simultaneously displayed on the screen. There were nine instances of the letter 'R' intermixed with distractor letters. The target letter occurred three times in the first line, four times in the second and two times in the third. Four 'R' were located on the left half of the paragraph, 5 on the right. A token of the 'R' letter to be searched for was presented during 5 s at the centre of the computer screen at the beginning of the experiment. The participants were instructed to search for all instances of the letter R, and to report the number of 'R' letters found. In both the reading and visual search tasks, stimuli were presented without time limitation. The recording stopped when the participant said "stop", and the number of letters he found was recorded.

3.1.3. Eye movements' analysis

To avoid interference due to the end of recording, the analysis only took into account those eye movements recorded on the three first lines of the text or text-like stimulus. Fixations shorter than 100 ms were removed from the recording files. The analysis was done on the right eye recordings for all participants, except three for whom left eye recordings were of better quality. Six oculomotor parameters were computed: total number of fixations, mean fixation duration, percentage of leftward (regressive) fixations, number of rightward fixations, rightward and leftward fixation duration. Another measure was computed as the total number of letters of the text or text-like stimulus divided by the number of rightward fixations. Although there is some overlap of information from fixation to fixation, this measure allows an on-line estimation of the number of letters simultaneously processed during each rightward fixation, thus providing an on-line estimation of the VA span.

4. Results

4.1. Performance analysis

In the visual search task, the dyslexic participants correctly identified 7.1 target letters ($SD = 1.3$) on average against 7.6 ($SD = 1.4$) for the normal-readers. The difference was not significant ($F < 1$).

Concerning time taken to perform the tasks, an ANOVA performed with GROUP (normal-readers/dyslexics) as between-subjects factor and TASK (Reading/Visual search) as within-subjects factor revealed a significant GROUP by TASK interaction ($F(1,26) = 18.26$; $p < .0001$). There was a significant main effect of GROUP ($F(1,26) = 15.84$; $p < .001$)—indicating that normal-readers were faster than dyslexics to perform the tasks (mean = 28 s; $SD = 13$ s and mean = 39 s; $SD = 12$, respectively)—as well as a main effect of TASK ($F(1,26) = 12.85$; $p < .01$) showing that more time was needed to perform the visual search (mean = 38 s; $SD = 9$ s) than the reading task (mean = 29 s; $SD = 15$ s). Planned comparisons revealed that the dyslexic participants performed the visual search task as quickly as normal-readers did (mean = 38 s; $SD = 9$ s and mean = 38 s; $SD = 10$, respectively; $F < 1$), but they read the text much more slowly (mean = 40 s; $SD = 14$ s vs. mean = 18 s; $SD = 3$ s; $F(1,26) = 31.08$; $p < .001$).

4.2. Eye movement patterns

Table 2 provides the oculomotor measures that characterise the eye movement patterns of the two groups in the reading and visual search tasks. Fig. 3 shows the eye movement pattern of a normal reader and a dyslexic reader in reading and visual search.

Rightward and leftward eye movement variables were submitted to ANOVAs with GROUP (normal-readers/dyslexics) as between-subjects factor and TASK (Reading/Visual search) as within-subjects factor. Log transformation of data was used when required to satisfy the homogeneity of variance assumption for ANOVAs.

4.3. Rightward eye movements

For rightward fixations, the GROUP by TASK interaction was significant ($F(1,26) = 16.18$; $p < .001$). The dyslexic readers made more rightward fixations than the controls (74.7 vs. 57.0; $F(1,26) = 19.98$; $p < .001$) and the participants as a whole made more rightward fixations in the visual search task than in the reading task (72.8 vs. 59.0; $F(1,26) = 18{,}80$; $p < .01$). Planned comparisons revealed that the dyslexic participants made more rightward fixations than the normal-readers in text reading ($F(1,26) = 43.35$; $p < .001$), whereas the number of rightward fixations of the two groups did not differ in visual search ($F < 1$). More precisely, the dyslexic participants keep making the same number of rightward fixations whatever the task ($F < 1$), whereas the normal readers made many fewer rightward fixations in reading than in visual search ($F(1,26) = 34.94$; $p < .001$; see Fig. 4).

Table 2
Means and standard deviations of the dyslexic and control group for the eye movement measures in visual search and reading tasks

		Dyslexics ($n = 14$)	Normal-readers ($n = 14$)
Visual search	Total number of fixations	109 (23)	107 (22)
	Mean fixation duration (ms)	323 (33)	328 (57)
	Number of rightward fixations	75 (13)	70 (16)
	Number of letters by rightward fixation	2.51 (0.5)	2.71 (0.54)
	Mean rightward fixation duration (ms)	324 (35)	332 (63)
	Number of leftward fixations	34 (15)	37 (12)
	Percentage of leftward fixations	30 (9)	34 (7)
	Mean leftward fixation duration (ms)	318 (46)	318 (61)
Reading	Total number of fixations	108 (22)	63 (13)
	Mean fixation duration (ms)	325 (86)	253 (25)
	Number of rightward fixations	74 (15)	44 (9)
	Number of letters by rightward fixation	2.56 (0.52)	4.34 (0.86)
	Mean rightward fixation duration (ms)	334 (93)	256 (27)
	Number of leftward fixations	34 (12)	19 (7)
	Percentage of leftward fixations	31 (8)	30 (7)
	Mean leftward fixation duration (ms)	302 (70)	248 (38)

As a consequence, a fewer letters were processed during a fixation in visual search than in reading and the number of letters processed by dyslexic readers was far lower in reading (2.56 vs. 4.34 for the controls) but comparable to that of normal readers in visual search (2.51 vs. 2.71).

For mean rightward fixation duration, analysis revealed a significant GROUP by TASK interaction ($F(1,26) = 9.02$; $p < .01$) and a significant main effect of TASK ($F(1,26) = 5.25$; $p < .05$) showing that mean rightward fixation duration was higher in the visual search task (mean = 330 ms; $SD = 50$ ms) than in the reading task (mean = 295 ms; $SD = 78$ ms). The main effect of Group was not significant ($F(1,26) = 3.90$; $p = .059$). Planned comparison analyses revealed that the mean duration of rightward fixations was longer in the dyslexic participants as compared to controls in reading ($F(1,26) = 9.13$; $p < .01$), despite a large overlap between the mean rightward fixation durations of the two groups. However, the two groups did not differ in their mean duration of rightward fixations ($F < 1$) in visual search. The dyslexic participants keep making rightward fixations of the same duration in reading and visual search ($F < 1$), whereas the normal readers made shorter fixations in reading ($F(1,26) = 14.01$; $p < .001$).

4.4. Leftward eye movements

Concerning leftward eye movements, analysis revealed a significant main effect of TASK ($F(1,26) = 16.02$; $p < .001$) showing that number of leftward fixations was higher in the visual search task (mean = 35; $SD = 14$) than in the reading task (mean = 26; $SD = 12$). The main effect of GROUP was not significant ($F(1,26) = 2.29$; $p = .14$). The GROUP by TASK interaction was significant ($F(1,26) = 17.89$; $p < .001$). As for rightward fixations, planned comparisons revealed that the dyslexic participants made more leftward fixations than the normal-readers in text reading ($F(1,26) = 9.13$; $p < .01$), whereas the number of leftward fixations of the two groups did not differ in visual search ($F < 1$).

The GROUP by TASK interaction on the percentage of leftward fixations was significant ($F(1,26) = 7.99$; $p < .01$). Normal-readers made a smaller percentage of leftward fixations in the reading task than in the visual search task, whereas the dyslexic children made the same proportion of leftward fixations whatever the task (the same proportion as normal-readers in visual search). None of the main effects of GROUP or TASK was significant.

The amplitude of regressive saccades was computed for each participant, after the three return sweeps had been removed. The mean amplitude was small and did not sig-

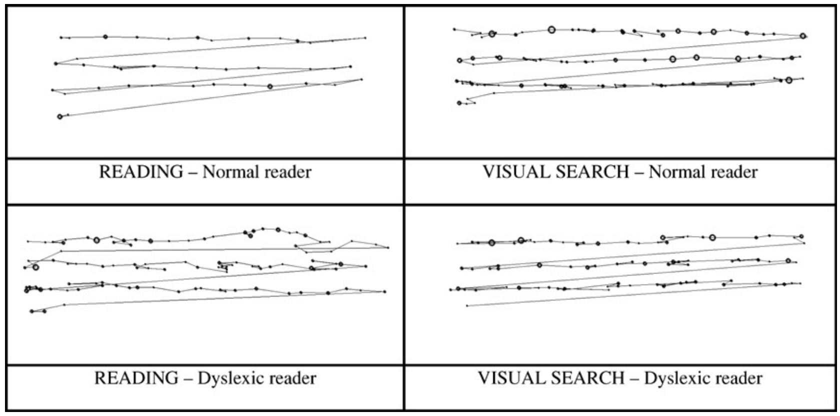

Fig. 3. The number and duration of fixations in *x*- and *y*-coordinates for a normal reader (top two panels) and a dyslexic reader (bottom two panels) in reading (left two panels) and visual search (right two panels). The size of each circle depicts the duration of each fixation.

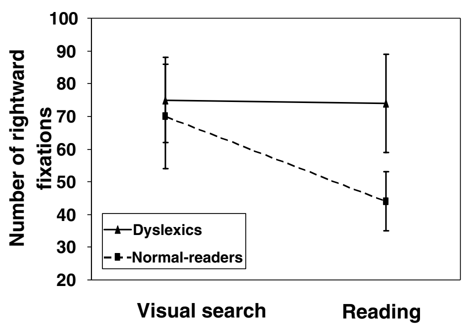

Fig. 4. Number of rightward fixations in visual search and reading in dyslexics and normal-readers.

nificantly differ between the two groups (1.37° vs. 1.41° in the dyslexics and normal-readers respectively; $F < 1$) or between the tasks (1.43° vs. 1.35° in the reading and visual search task respectively; $F < 1$). These findings suggest that leftward fixations probably result from oculo-motor landing errors rather than being linguistically justified. The analysis conducted on mean leftward fixation duration revealed no main effect of GROUP ($F(1,26) = 2.33$; $p = .14$) but a significant main effect of TASK: mean leftward fixation duration was longer in visual search than in reading (321 ms in the visual search task, vs. 275 ms in the reading task; $F(1,26) = 14.80$; $p < .001$). The GROUP by TASK interaction was significant ($F(1,26) = 5.68$; $p < .05$). Planned comparisons revealed that the dyslexic participants made longer leftward fixations than the normal-readers in text reading ($F(1,26) = 6.30$; $p < .05$), whereas the duration of leftward fixations of the two groups did not differ in visual search ($F < 1$).

4.5. Correlation analyses

According to our hypotheses, a negative correlation was expected between the number of rightward fixations as assessed during reading and the VA span as estimated off-line through the global and partial report tasks. No a priori correlation was expected with the percentage of leftward fixations. Because of the well known relationship between learning to read and phoneme awareness (Castles & Coltheart, 2004; Vellutino, Fletcher, Snowling, & Scanlon, 2004), the potential existence of a relationship between the oculomotor measures and the children's phoneme awareness skills was also assessed.

Table 3
Pearson's correlation coefficients between age, scores on the off-line tasks and eye movement measures in visual search and reading tasks

	Visual search			Reading		
	Number of rightward fixations	Number of leftward fixations	Percentage of leftward fixations	Number of rightward fixations	Number of leftward fixations	Percentage of leftward fixations
Age	−0.08	−0.27	−0.30	0.24	0.09	−0.09
VA span	−0.27	−0.01	0.15	−0.70***	−0.58**	−0.13
Global report	−0.08	0.12	0.18	−0.72***	−0.63***	−0.17
Partial report	−0.44*	−0.15	0.09	−0.56**	−0.44*	−0.07
Phonological score	0.11	0.15	0.08	−0.01	0.06	0.07
Phoneme segmentation	0.06	0.14	0.08	0.17	0.34	0.25
Phoneme deletion	0.13	0.11	0.05	−0.21	−0.26	−0.14

* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 3 shows the intercorrelations between the relevant eye movement measures assessed in reading and visual search, and the measures of VA span and phoneme awareness.

The VA span and the number of rightward fixations correlate significantly and negatively in reading, but not in visual search. In reading, both global and partial report scores correlate with the number of rightward fixations, whereas the partial report score alone relates to the number of rightward fixations in visual search. However and unexpectedly, the VA span (both global and partial report scores) was further found to correlate with the number of leftward fixations in reading, but not in visual search. It is noteworthy that the numbers of rightward and leftward fixations are not strictly independent measures since after a leftward fixation, there has to be a rightward fixation to return the eyes to the target word or letter. Accordingly, partial correlations were further calculated to assess whether the VA span still correlated with the number of rightward fixations after the number of leftward fixations was partialled out. Results revealed that the correlation between VA span and number of rightward fixations remained significant after control for the number of leftward fixations (partial correlation $r = .44$; $p < .05$). With respect to the percentage of leftward fixations, no correlation was found with the VA span in either task. In addition, none of the measures of phoneme awareness (or age) related to the eye movement measures.

5. Discussion

The aim of the present study was to show that VA span abilities have an impact on eye movement patterns. More specifically, two main consequences of a VA span disorder in dyslexic readers were proposed and subsequently investigated. It was first expected that a VA span reduction should manifest itself during reading in more frequent rightward fixations. The VA span disorder was expected to have a similar impact on visual search, if the two tasks were similarly processed by non-dyslexic children. However, the VA span disorder should differently impact eye movement patterns in reading and visual search if the visual attentional demands of the tasks differed.

The French dyslexic readers used in this study were selected a priori for having a VA span disorder in the absence of phoneme awareness problems. They demonstrated a higher number of rightward and leftward fixations than control readers of the same chronological age in reading as well as longer fixation durations. Their eye movement pattern in reading thus conformed to that typically reported in unselected samples of dyslexic individuals (for a review, see Rayner, 1998). Also in agreement with previous reports, the present study did not reveal any differences in the eye movement patterns of dyslexic and control readers during visual search, although the consonant strings presented in this latter task had the same visuo-perceptual and visuo-spatial characteristics as text reading. This latter finding brings additional support to the view that dyslexics' atypical movement patterns in reading cannot be explained in terms of oculomotor or visual perceptual problems (De Luca et al., 1999; Hutzler et al., 2006; Trauzettel-Klosinski et al., 2002). However, atypical eye movements in reading were highlighted in a subgroup of dyslexic children without phoneme awareness problems, so that any interpretation in phonological terms was rather unlikely.

An important finding of the present research is to show that control readers do not process strings of letters similarly in the two tasks. Indeed, normal readers exhibit a higher number of rightward fixations in visual search than in reading, thus indicating that the number of letters processed during each rightward fixation is far higher in reading than in visual search (here estimated at 4.34 letters on average in reading against 2.71 in visual search). This finding suggests that normal readers adapt the number of letters simultaneously processed according to the task. In contrast, the dyslexic participants only processed a few letters during each rightward fixation and the number of processed letters was similar in reading and in visual search (2.56 and 2.51, respectively). In accordance with the fact that the dyslexic's VA span as evaluated off-line was reduced, such findings suggest that, contrary to normal readers, dyslexic children can only process a few letters at each fixation and cannot increase the number of letters processed in a reading task as compared to a non-reading task.

A second important result is that the number of rightward fixations relates to VA span, in reading but not in visual search. The more reduced the VA span, the higher the number of rightward fixations in reading and thus the higher is the probability for the text to be read analytically. The present findings thus suggest that the dyslexic participants' VA span disorder prevents them for processing as many letters simultaneously as normal readers do in reading. However, the dyslexic readers are not disadvantaged by their VA span reduction in visual search since the number of letters processed by normal readers in this latter task is reduced at a similar level. The VA span was found to relate specifically to the number of fixations, whereas fixation duration does not seem to be primarily determined by the number of letters to be processed, since longer duration fixations were found in visual search than in reading whereas fewer letters were simultaneously processed by normal readers in the former task.

The present findings suggest that even tasks which are very similar at the visuo-perceptual or visuo-spatial level do not necessarily pose similar demands on visual processing. In the current study, scores in both global and partial report were found to correlate with the number of rightward saccades in reading. This suggests that the reading task, as the two report tasks, requires attention to be distributed on as many letters as possible for their subsequent identification (see Valdois, Bosse, & Tainturier, 2004 or Bosse et al., 2007, for a description of the tasks). The cognitive demands of the visual search task differ in requiring a single target to be identified and counted. This task probably shares some characteristics with the partial report task alone which at a second step requires selective attention to focus on the cued letter which alone has to be identified.

In the current study, the dyslexic population was a priori selected for having no phonological problems. Thus, the absence of relationship between the phonological scores and eye movement measures may just result from the small variation of phoneme awareness performance in the selected sample of dyslexic children. The dyslexic participants' higher number of rightward fixations was found here to correlate with their VA span as expected following the multitrace memory model's predictions. This finding is compatible with the predicted causal relationship between VA span and number of rightward fixations. However, a causal relationship would require demonstrating that the VA span reduction is not just a consequence of the poor reading level of the dyslexic participants (Bryant & Impey, 1986). Previous findings revealed that this is not usually the case and that dyslexic children with a VA span disorder typically show a more reduced VA span than younger non-dyslexic children matched for reading age (Bosse & Valdois, 2003; Valdois et al., 2003). No reading age control group was used in the current study because of the technical constraints imposed by eye movement recordings. Further research is thus required to confirm that the co-occurrence of a reduced VA span and a higher number of rightward fixations does not just follow from the poor reading outcome of dyslexic readers. It is further noteworthy that the current findings do not rule out the possibility for other dimensions apart from the VA span (such as phonological skills or other psycholinguistic dimensions) to affect eye movement patterns. They however strongly suggest that the heterogeneity of the dyslexic population is a relevant factor and that the nature of the underlying impairments might differentially affect eye movement patterns in different subgroups of dyslexic children.

6. Conclusions

The atypical eye movement patterns of dyslexic children in reading do not seem to result from a primary oculomotor disorder, even when children are a priori selected for having visual processing problems. More importantly, the present findings suggest that the poor VA span abilities of dyslexic children might contribute to their atypical eye movement patterns, in increasing the number of rightward fixations during text reading. However, this disorder has no impact on the visual search task which poses different requests in terms of visual attentional processing. A VA span disorder resulting in more fixations could well account for the tendency of some dyslexic children to read analytically. Further studies are needed to determine whether subgroups characterised by distinct underlying cognitive disorders also differ with respect to their oculomotor patterns.

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