Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia

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Abstract

Ten subjects who could be reliably assessed as surface dyslexics were selected on the basis of a large test battery. Eye movements in non-linguistic and linguistic tasks were studied in these subjects.

Stability of fixation on a stationary stimulus was examined. Performance of dyslexics was no different from that of an age-matched control group. Similarly, no difference was observed between the two groups when they were requested to saccade to a rightward or leftward target. On the other hand, while reading short passages, dyslexics showed an altered pattern of eye movements with more frequent and smaller rightward saccades as well as longer fixation times. The reading pattern was analysed by eye tracking. Numerous fixations were used to read a single word in a fragmented way. Longer words showed a higher number of fixations.

Overall, it was concluded that surface dyslexia is not associated with oculo-motor dysfunction and the study of eye movements in reading reveals the processing through orthography-to-phonology conversion characteristic of surface dyslexia. The importance is stressed of examining selected groups of subjects in the psychophysiological study of dyslexia. © 1999 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Surface dyslexia; Development; Eye movements; Reading; Fixation stability; Eye tracking

1. Introduction

In the study of dyslexia, great effort has been devoted to the analysis of eye movements in reading. Differences in eye movement pattern with respect to that typically exhibited by expert readers were already noted in the 1950s [37]. Later, more refined techniques, involving measurement of the number and duration of fixations during reading, allowed for quantitative comparisons of dyslexics and normal readers. Both parameters were altered in dyslexics: the number of forward saccades was higher and the fixation duration was longer [1]. Occasionally, a conspicuous increase in regressions (backward saccades) was also reported [25].

Eye movement abnormalities in dyslexics may be considered a consequence of defective processing of verbal material; in this case, they are secondary to the linguistic problem. This view has a long tradition [6] and a broad consensus [20,21] and is based on two main types of evidence. Firstly, while more frequent, saccades during reading show normal morphology [1]. Secondly, differences in frequency between dyslexics and normal readers disappear if the latter group is compared to a group matched for reading age rather than for chronological age [21]. However, the opposite view has also been proposed [26], that is, oculomotor
function is altered in dyslexics causing (or contributing to) reading difficulties. In fact, a deeply altered pattern of eye movements in a non-reading visual task was reported in dyslexic subjects [26].

The question is still unresolved. In fact, while most subsequent research has failed to replicate the dramatic impairments reported by Pavlidis [3, 4, 21, 22, 35], subtle alterations in eye movement patterns in non-reading tasks have also been reported. Saccadic intrusions during smooth pursuit [1, 36], fixation instability, poor vergence, jerking eye movements in pursuit and loss of smoothness in left to right saccades [12] were reported in dyslexics. In particular, Eden and colleagues [12] found that saccade and smooth pursuit defects in non-reading tasks were moderately correlated with reading ability and suggested they might be potentially useful predictors of reading level. On the basis of this evidence, they concluded that a deficit in the control of eye movements cannot only be explained by linguistic factors. Further, saccadic reaction times were found to be abnormal in dyslexics, with a larger number of express saccades [13]. In a different study [2], different types of saccade alterations were described for dyslexics with or without additional general cognitive dysfunctions.

The possibility that variability in eye movement deficits among dyslexics might depend on sampling characteristics has been suggested repeatedly to explain the discrepancy between general findings and Pavlidis' data [27] (see also [12]). For example, a number of authors have commented upon the different selection criteria used in the Pavlidis study as opposed to the (failed) replications [27]. However, with few exceptions [23], this has not led to a systematic evaluation of the potentially important individual differences. Rather, most research on the psychophysiological correlates of dyslexia, including the study of eye movements, has considered these subjects as a single, homogeneous group. Much to the contrary, an impressive amount of cognitive literature has persuasively shown that there are at least two types of developmental dyslexia [7]. In phonological dyslexia, children have problems in the phonological translation of orthographic symbols. The most characteristic sign of the deficit is their selective inability to read non-words (i.e., pronounceable strings of letters that cannot be read with reference to an internal visual lexicon and require the child to correctly master the rules of orthography-to-phonology conversion). In surface dyslexia, the deficit is in access to the direct lexical route; this provokes a selective deficit in reading irregular words (such as yacht) that cannot be read through the orthography-to-phonology conversion and require access to a visually defined lexical entry [24]. Similarly, these subjects have problems in tasks requiring appropriate visual evaluation of stimuli, such as discriminating homophones or assigning the appropriate stress to words. Overall, defective reading can be due to the selective impairment of two different (lexical or sub-lexical) processes; however, the possibility of a proportion of mixed cases should also be considered.

The existence of two subgroups of developmental dyslexia may help in clarifying inconsistencies in reports on dyslexia, particularly in the case of studies based on children speaking different languages.

In fact, the two types of disturbances may be prevalent in different degrees in different languages depending on the regularity of their spelling–sound correspondences. In English-speaking countries, it is well established that phonological dyslexia is largely prevalent (about two-thirds of dyslexics have problems in the phonological translation of orthographic symbols; [7]). On the contrary, this deficit might be silent in other languages, such as Italian and German, which have more regular spelling–sound correspondences [40]. For example, there are only exceptional reports of children with phonological dyslexia among Italian children [31]. Thus, it has been proposed that the asymmetrical composition of different types of dyslexia in studies based on different languages may bias the results over and above the effect of the experimental task studies [34]. Further, a pre-selection of dyslexics based on the nature of their reading disorder may be crucial for explaining at least part of the reported differences. For instance, in a recent psychophysical study on a selected group of Italian surface dyslexics [34] no deficit was found in the transient visual system. This result is in contrast with most studies on English-speaking children where an impairment of this system has been observed [19] but is in agreement with a study on German-speaking children [39].

In the present research, we selected a group of Italian subjects who could be reliably described as surface dyslexics according to standard cognitive criteria. Our aim was to characterise their eye movement pattern during reading and evaluate whether possible alterations could be observed also in non-linguistic tasks, pointing to the presence of a more basic oculomotor disturbance. As mentioned above, the literature on non-linguistic tasks is controversial, making the selection of appropriate tasks difficult. Our choice was guided by the observation that in reading an alteration of both fixation duration and saccade length has been reliably reported in dyslexics [1, 21]. Consequently, it seemed useful to employ tasks which may conceivably have a relationship with these two components of eye movement behaviour known to be controlled by separate mechanisms [29]. In one condition, fixation stability was evaluated [12]; the ability to hold fixation on a stationary spot may be considered a necessary prerequisite of appropriate fixation during reading. In another condition, developed by Pavlidis [26], saccades...
to a target displayed in a rightward and leftward direction were examined. The ability to program a saccade of the correct size in such a simple task may be considered a necessary prerequisite for appropriate saccade control during reading.

2. Methods

2.1. Subjects

Subjects were referred to us either directly or by school teachers. Criteria for inclusion in the sample were marked reading delay on a standard reading test (see below), IQ level within 1 SD of normal limits, a reading pattern coherent with the diagnosis of surface dyslexia, normal or corrected to normal visual acuity and absence of severe refractive errors. The final sample included 10 subjects (8 males and 2 females). Nine subjects were middle school students, and one (D.I.) was older and attended high school. Ages ranged from 10.11 to 17.11 years and months (mean = 12.6 years; SD = 2.0). Intelligence was evaluated by the WISC scale (WAIS in the case of D.I.). Full scale IQs ranged from 85 to 127 (mean = 95.3; SD = 13.7). The subjects had 10/10 (range 10–11) mean visual acuity. Individual data are presented in Table 1.

For the fixation task and the rightward-leftward saccade task, dyslexics were compared to a control group comprised of 11 children without reading problems. Since there was only one older pathological subject we chose to have a control group that approximately matched the age of the remaining 9 dyslexics (mean age = 11.8 years; SD = 1.4). A different group of ten children served as controls for eye movements during the reading task (mean age = 10.5 years; SD = 1.0). A third group of twenty 11.1- to 16.0-year-old subjects served as control subjects (mean age = 12.7; SD 1.6 years) for the Phonemic Awareness test. Reading level in these three groups of control subjects was assessed by the use of the MT reading test (see below).

2.2. Assessment of reading

Reading level was examined with a standard reading achievement test (MT Reading test [10]). Two meaningful passages were presented. In the first, the subject had to read aloud (with a 4 min time limit); speed (time in s per syllable read) and correctness (number of errors, adjusted for the amount of text read) were scored. A second passage was given without a time limit; the subject had to read it and respond to 10 multiple-choice questions (measure of comprehension). Stimulus materials (and related reference norms) varied depending on school level up to the third class of middle school. Above this level, reading speed and accuracy are expected to reach a plateau and only subtests for testing comprehension are used. Thus, although D.I. was in High School at the time of testing, we chose to use the final tests of the middle school third class. However, comprehension was also examined in this subject using the Advanced MT Comprehension in Reading test [11]. This comprises 90 items with multiple-choice alternatives and is adapted for use with 13–16-year-old subjects. Time to complete the test was recorded but no time limit was given.

The nature of the reading disturbance was examined by means of the Developmental dyslexia and dysorthography battery [32]. A screening subtest (Reading graphemes) requires the subject to read aloud 21 single letters. Two sub-tests with homophones were then given. In one (Comprehension of homophones) the subject is required to choose the correct item from among four alternatives such as the following: ‘l’ago è fatto di acqua, legno, terra, ferro’ (‘The needle is made of water, wood, ground, iron’). ‘L’ago’ (‘the needle’) has the same sound but a different meaning from ‘lago’ (‘lake’). Twenty-four trials were given. The subject’s

Table 1

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age</th>
<th>Sex</th>
<th>Class</th>
<th>Visual acuity</th>
<th>Verbal IQ</th>
<th>Performance IQ</th>
<th>Full scale IQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.S.</td>
<td>10.11</td>
<td>M</td>
<td>1st year Middle School</td>
<td>11/10</td>
<td>82</td>
<td>93</td>
<td>87</td>
</tr>
<tr>
<td>O.A.</td>
<td>11.4</td>
<td>M</td>
<td>1st year Middle School</td>
<td>11/10</td>
<td>86</td>
<td>95</td>
<td>89</td>
</tr>
<tr>
<td>F.C.</td>
<td>11.6</td>
<td>M</td>
<td>1st year Middle School</td>
<td>11/10</td>
<td>92</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>L.R.</td>
<td>11.10</td>
<td>F</td>
<td>1st year Middle School</td>
<td>11/10</td>
<td>78</td>
<td>101</td>
<td>87</td>
</tr>
<tr>
<td>R.D.</td>
<td>12.1</td>
<td>M</td>
<td>1st year Middle School</td>
<td>10/10</td>
<td>91</td>
<td>88</td>
<td>89</td>
</tr>
<tr>
<td>L.M.</td>
<td>12.7</td>
<td>M</td>
<td>1st year Middle School</td>
<td>10/10</td>
<td>91</td>
<td>81</td>
<td>85</td>
</tr>
<tr>
<td>A.J.</td>
<td>13.2</td>
<td>M</td>
<td>1st year Middle School</td>
<td>11/10</td>
<td>84</td>
<td>112</td>
<td>96</td>
</tr>
<tr>
<td>D.B.</td>
<td>11.10</td>
<td>M</td>
<td>2nd year Middle School</td>
<td>10/10</td>
<td>119</td>
<td>130</td>
<td>127</td>
</tr>
<tr>
<td>G.L.</td>
<td>11.11</td>
<td>M</td>
<td>2nd year Middle School</td>
<td>10/10</td>
<td>88</td>
<td>93</td>
<td>90</td>
</tr>
<tr>
<td>D.I.</td>
<td>17.11</td>
<td>F</td>
<td>5th year High School</td>
<td>10/10</td>
<td>106a</td>
<td>125a</td>
<td>114a</td>
</tr>
</tbody>
</table>

* WAIS scale.
performance was expressed with the following formula [30]:

\[
\frac{\text{homophonic errors}}{\text{homophonic errors} + \text{correct responses}} \times 100
\]

Scores near 50 indicate chance performance. Non-homophonic errors are noted to establish performance validity but are not considered in the computation.

In the other subtest (Discrimination of homophonic sentences), the subject is given a list of 20 short sentences (e.g., ‘I monaci abitano nel convento’ or ‘I monaci abitano nel con vento’; ‘The monks live in a monastery’ or ‘The monks live in with wind’) and is required to indicate whether or not they are correct. Again, this task cannot be solved by referring to a grapheme-phoneme conversion and visual analysis of stimuli is required. The percentage of errors is computed (50% = chance performance). A stress assignment subtest comprises the presentation of a list of 60 three-syllable words. Thirty-three have the stress on the next to last syllable (assumed as the norm in the Italian language) and 27 on the first syllable (taken as the exception to the rule). Only stress assignment errors were considered in this subtest. Two other subtests checked the reading of words and non-words. A list of 112 words was presented and the subject was required to read them aloud. A similar list of 48 non-words was presented. Number of errors and speed of reading were scored.

2.3. Phonemic awareness

The phonemic awareness of the dyslexics was measured with a Phonemic blending test [38]. A set of twenty 3–8-letter words was used. The examiner read the phonemes of each word at the rate of one per sec. The subject’s task was to report the word. The score was the number of correct fusions of at least two phonemes. (e.g., C/A/N/E: CA = 1 point; NE = 1 point; ANE = 2 points; CANE = 3 points). Maximum score was 84.

2.4. Eye movement recordings

Eye movements were recorded in three experimental conditions: (a) during a fixation task; (b) in a rightward-leftward saccade task and (c) while reading brief passages.

2.5. Apparatus and general procedure

Eye movements were recorded by means of an infrared pupil reflection system (AMTech ET3 eye tracking system). This enables measuring movements in both horizontal and vertical directions for one eye. The sampling rate was 200 Hz. The system has an absolute accuracy of 0.25°. The subjects sat on a chair; a headrest and a chinrest were used to keep their heads immobile during recording. The subjects were requested to stay as still as possible and to try not to blink during the recording period. Stimuli were presented on the screen of a PC computer. The viewing distance was 60 cm.

A calibration procedure was carried out. The subject was requested to fixate a target (a little square) which was displayed in different successive positions on the screen according to a pre-selected matrix. The matrix was 2 × 2 for the first two conditions (fixation and saccade tasks) and 3 × 3 for the reading condition (see below). After fixation of the first square, the target disappeared and a new target appeared in the next position. The subject’s task was to saccade to the next position etc. The experimental task (see below) was performed immediately after calibration. Calibration was repeated before each trial.

The portion of the trace contaminated by artefacts due to blinks was signalled by the computer and rejected. Artefacts due to occasional head movements were rejected. Only artefact-free recordings were used.

2.6. Fixation task

2.6.1. Stimulus and procedure

The stimulus was a white dot on a dark background subtending 0.5°. The dot was displayed in the center of the screen for 10 s. The task was to fixate the dot steadily. The stimulus was presented three times. Calibration was based on four different positions on the screen according to a 2 × 2 matrix spanning 20.2° horizontally and 16° vertically.

2.6.2. Analysis

Eye position was recorded every 5 ms for the 10-s period. The measure was the variation of the position of the eye (in degrees), calculated separately for the horizontal and vertical eye movement components. Data were averaged in two 5-s intervals. Moreover, an additional analysis was made, limited to the data collected in the first 500 ms.

2.7. Rightward-leftward saccade task

2.7.1. Stimuli and procedure

The stimulus was a black dot on a light background. The dot subtended 0.2° of visual angle and appeared in five different positions on the horizontal meridian. Firstly, the dot appeared on the left side of the screen; then it disappeared and appeared 4° horizontally to the right. This was repeated for the successive positions. The fifth position was the rightmost; then the sequence was repeated in the leftward direction. The
duration of the first and fifth dots was 2 s, and that of
the second, third and fourth dots was 1 s. The right-
ward and leftward sequences were repeated twice in
each trial. The subject’s task was to saccade to the dot
as soon as it appeared. Three trials were given.
Calibration was the same as for the fixation task.

2.7.2. Analysis
The eye movement measurements included various
parameters. The amplitude (in degrees) of the right-
ward saccades during rightward tracking and of left-
ward saccades during leftward tracking was consid-
ered. Moreover, in the case of hypometric sac-
cades, the percentage of additional forward saccades
with respect to the number of forward saccades during
rightward tracking and during leftward tracking was
computed. In cases of over-shooting saccades we con-
considered the percentage of additional backward saccades
with respect to the number of saccades during right-
ward tracking and during leftward tracking.
Inspection of the traces indicated that sometimes the
observers made the saccadic movement before the tar-
get onset. Anticipations were present in both groups of
subjects and were not considered in the analysis.

2.8. Reading task

2.8.1. Stimuli and procedure
Stimuli were short passages (black letters on a light
background). Fourteen passages containing an average
of 30.6 (SD = 1.6) words were presented. Passages were
composed in such a way that the frequency of content
words was homogeneous (median frequency = 3808)
[15]. There was no difference in frequency values in the
14 passages (Kruskal Wallis $H_{(13)} = 7.34$, n.s.).
The character width (or center-to-center spacing of
characters) was 0.5° on the average. Each passage was
composed so as to contain 4 lines (7.6 words per line,
SD = 1.3; center-to-center line distance = 1.4°) and was
fully displayed on the screen without a time limit.
The text was 21.4° wide and 6.2° high. The subject’s task
was to read the passages silently. After reading each
passage, the children were asked a few questions to
evaluate their comprehension. Calibration was based
on nine different positions on the screen according to a
$3 \times 3$ matrix spanning 21.4° horizontally and 6.2° ver-
tically.

2.8.2. Analysis
Two types of analyses were performed. Firstly, six
major parameters of eye movements in reading were
calculated on the overall recordings. The parameters
were: number of rightward saccades per line; ampli-
tude of rightward saccades (in degrees); number of re-
gressions per line; amplitude of regressions (in
degrees); percentage of regressions on total saccades;
and fixation duration (in ms). As noted above, the sub-
jects read 14 passages. However, only those passages
for which a reliable recording was obtained were sub-
mitted to further analysis. In the case of the dyslexic
children, an average of 6.1 passages (SD = 1.4) were
considered and for control subjects, an average of 7.4
passages (SD = 1.4).

A second type of analysis was concerned with the
eye movements in reading as a function of text charac-
teristics. The number of fixations per word made by
each subject as a function of the length and frequency
of each word was computed. This type of analysis
requires placing individual fixations with respect to the
actual words presented. To examine relatively homo-
geneous samples of items, only content words were
considered in this analysis. Due to the use of sentences
instead of single words only two categories of length
(short, 4–5 letter words, and long, 6–8 letter words)
and two categories of word frequency (high and low,
with respect to the median value of frequency) could
be reliably assessed. In general, only the part of the
traces for which fixations could be reliably superim-
posed on the words were considered. For the dyslexic
group, an average of 7.0 (high frequency-short), 6.7
(low frequency-short), 13.6 (high frequency-long) and
15.0 (low frequency-long) words were reliably scored.
Values were very similar in the group of control sub-
jects: 8.0 (high frequency-short); 7.2 (low frequency-
short); 12.8 (high frequency-long) and 14.2 (low fre-
quency-long).

3. Results

3.1. Assessment of reading
The subjects in the control groups were examined
for reading level using the MT battery. Their perform-
ances were always within normal limits for all three
parameters considered (comprehension, speed and ac-
curacy).

The individual performances of the dyslexics on the
reading tests are presented in Tables 2 and 3 along
with the normative data for different class levels. Note
that for comprehension, D.I. was compared with
norms of her appropriate age [11]; for all other tests,
normative data for her age were not available and
data from the last class of the middle school are pre-
sented (about 5 years younger).

On the MT Reading test, all subjects were deficient
in reading speed compared to standard norms. Note
that for the seven dyslexics in the first class and the
two in the second class reading time was longer than
expected by a factor ranging from about 2 to 6. Note
also that the oldest subject (D.I.) was out of the nor-
mal limits, although she was compared here to norms
for subjects approximately five years younger. A similar pattern emerged for number of errors, with only two subjects (D.B. and D.I.) performing within normal limits. On the other hand, only four subjects showed a deficit in comprehension, indicating that, even with their slow and laborious reading, several of these subjects could comprehend the meaning of a text.

Performances on the Developmental dyslexia and dysorthography battery (shown in Table 3) qualified the nature of the reading disorder in these subjects. Firstly, reading of single graphemes was entirely faultless in all subjects (not shown). A dramatic deficit (chance level) in the comprehension of homophones sub-test was shown by all young subjects. Non-homophonic errors were infrequent in all subjects (mean = 7.9%), indicating that performances could not be explained by a general comprehension deficit. D.I.’s performance was well above chance; however, her score was about twice as bad as that of subjects in the third year of middle school (ca. five years younger) indicating very poor performance in this test [33]. Stress assignment errors were present in all subjects, although

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>Reading performance in the MT Reading test battery⁴</td>
</tr>
<tr>
<td>Subject</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>C.S.</td>
</tr>
<tr>
<td>O.A.</td>
</tr>
<tr>
<td>F.C.</td>
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<tr>
<td>L.R.</td>
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<tr>
<td>R.D.</td>
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<tr>
<td>L.M.</td>
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<tr>
<td>A.J.</td>
</tr>
<tr>
<td>1st middle class</td>
</tr>
<tr>
<td>D.B.</td>
</tr>
<tr>
<td>G.L.</td>
</tr>
<tr>
<td>2nd middle class</td>
</tr>
<tr>
<td>D.I.</td>
</tr>
<tr>
<td>3rd middle class</td>
</tr>
<tr>
<td>Advanced MT</td>
</tr>
</tbody>
</table>

- For the comprehension of homophonic words sub-test, reference data are from Scalisi and Berardi [33]; for all other tests, normative data are from Sartori, Job and Tressoldi [32]. N was 262 for the 1st year of Middle School, 296 for the 2nd year and 181 for the 3rd year, respectively.
- In this subject, comprehension was tested with the Advanced MT Comprehension in Reading test. Form A. Reference data refer to a sample of 345 subjects [11].
- Request for attention.
- Immediate intervention.

<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading performance in the Developmental dyslexia and disorthography battery⁴</td>
</tr>
<tr>
<td>Subjects</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>C.S.</td>
</tr>
<tr>
<td>O.A.</td>
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<tr>
<td>F.C.</td>
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<td>L.R.</td>
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<td>R.D.</td>
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<tr>
<td>L.M.</td>
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<tr>
<td>A.J.</td>
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<tr>
<td>1st middle class</td>
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<tr>
<td>D.B.</td>
</tr>
<tr>
<td>G.L.</td>
</tr>
<tr>
<td>2nd middle class</td>
</tr>
<tr>
<td>D.I.</td>
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<tr>
<td>3rd middle class</td>
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</tbody>
</table>

- For the comprehension of homophonic words sub-test, reference data are from Scalisi and Berardi [33]; for all other tests, normative data are from Sartori, Job and Tressoldi [32]. N was 31 for the 1st year of middle school, 55 for the 2nd year and 52 for the 3rd year for the Scalisi and Berardi [33] sample. In the case of Sartori, Job and Tressoldi [32], N was 129, 102 and 125, respectively.
- 50 = chance level.
- Performance at or below the fifth percentile.
3.2. Phonemic awareness

Median performance of controls in the phonemic blending test was 82 (range 73–84); for the dyslexic subjects the median was 76.5 (range 51–84) (Mann–Whitney $U = 45.5, z = -2.41, P < 0.05$). Seven dyslexics scored within the control range and three below it (F.C. = 62; R.D. = 51; G.L. = 63).

3.3. Comments

All young subjects were able to read individual letters but were dramatically deficient in discriminating homophones. This is a characteristic marker of the inability to process the stimulus via the direct lexical visual route [17]. In general, performance in reading non-words was lower than for words, both for speed and errors. However, in relative terms the ability of dyslexics to read words versus non-words was comparable to that of normal subjects [18]. This does not support the idea that processing non-words was particularly defective in this group of subjects, as would be expected in phonological dyslexia. However, considering the wide difference in performances between the pathological group and the controls and the presence of some cases of defective phonological skills, it cannot be excluded that some dyslexics also show an impairment in sub-lexical routines. The presence of additional sub-lexical deficits in surface dyslexia has already been reported in both English-speaking [9] and Italian dyslexic subjects [17]. In discussing these cases, Castles and Coltheart [7] emphasised the importance of considering the relative difference in efficiency between the lexical and sub-lexical procedures. Overall, it seems conservative to conclude that the present group of subjects show a more prominent deficit in the use of the lexical route, consistently with a diagnosis of surface dyslexia.

Besides typical reading errors, a characteristic of these subjects is reading slowness. Reading speed is usually not stressed in cognitive descriptions of dyslexia in English-speaking subjects that are typically based only on an analysis of the pattern of errors. However, slowness may be the most prominent feature of the reading disorder in languages with regular spelling–sound correspondence [40,41]. In fact, examining the written material through an orthography-to-phono- nology conversion, the subject progresses slowly and laboriously; depending on the characteristics of the language and the level of optimisation of this reading strategy, he/she may in fact be able to read slowly but rather correctly except in cases requiring a global visual analysis, such as in the case of homophones (which are very rare in Italian).

Although D.I. is 7–8 years older than the other dyslexic subjects, her general reading performance was very similar. She read slowly with few errors, making a significant (although small) number of errors in homophones and in stress assignment. No clear deficit was apparent for reading non-words (either in errors or speed). Text comprehension was also well within normal limits for her age level. Some authors [5] have proposed that surface dyslexia may simply express a temporal lag in reading achievement (see Ref. [8] for a discussion of the opposing arguments on this point). This view does not correspond with D.I.’s performance and, in particular, cannot account for the dissociation between reading slowness, which is severe, and the ability to extract meaning from the text, which is essentially normal. Rather, it appears more reasonable to posit that this subject has remained anchored to a single reading process (orthography-to-phono- nology conversion) and has reached a level of ability which is probably near the maximum that can be obtained through this mode of processing.

3.4. Eye movements

3.4.1. Fixation task

Individual mean data are presented in Fig. 1 as a function of group, time (first-last 5 s intervals) and vertical-horizontal components of eye displacement. It is evident from the figure that the two groups were quite similar across conditions.

An ANOVA with group (controls, dyslexics) as unpeated factor and directional component of eye displacement (vertical, horizontal) and time (first 5 s vs
last 5 s) as repeated factors showed no reliable main effect for group \((F_{1, 19} < 1)\), direction \((F_{1, 19} < 1)\) or time \((F_{1, 19} = 1.69, \text{n.s.})\). All interactions were non significant.

A separate ANOVA with group (controls, dyslexics) and direction component of eye movement (vertical, horizontal) was performed on the values of the first 500 ms of fixation. The aim was to evaluate fixation stability for a time range relatively close to that of fixations during reading. The effect of group was not significant \((F_{1, 19} < 1)\); the effect of direction \((F_{1, 19} = 10.47, P < 0.01)\) showed greater instability in the horizontal \((0.15^\circ)\) than in the vertical direction \((0.12^\circ)\) for this time interval. The group \(x\) direction interaction was not significant \((F_{1, 19} < 1)\).

3.4.2. Comments

The present results do not provide any support for the idea that fixation instability is a characteristic peculiar to surface dyslexics. In an in-depth study of fixation, Eden et al. [12] showed poor fixation in dyslexics in a relatively similar task. There may be many reasons for this different outcome. Firstly, in Eden et al.’s study [12], an unselected group of dyslexics was examined; since most were reported to have phonological problems, this may indicate that phonological dyslexia is associated with unstable fixation. Moreover, procedural differences in testing in the two studies may have been potentially important (including binocular vs monocular viewing, differences in target size and in viewing distances).

In light of these considerations, caution should be taken in generalising the present results to the population of dyslexics. However, it should be considered that in our study fixation stability was evaluated with the same general set-up as the reading task (in terms of distance, eye tested and stimulus size). Therefore, it appears extremely unlikely that fixation instability per se is a significant factor in the reading deficit in the present sample of surface dyslexics.

3.5. Rightward-leftward saccade task

Results obtained in this task are presented in Fig. 2. In general, most saccades of both control subjects and dyslexics were slightly on undershooting (smaller than 4°). The mean amplitude of rightward and leftward saccades for individual controls and dyslexics is reported in Fig. 2a. Inspection of the figure indicates a large overlap between the two groups; one control and one dyslexic (L.M.) undershot the target considerably in the rightward direction.

This is confirmed by an ANOVA with group (controls, dyslexics) as unpeated factor and direction (rightward, leftward) as repeated factor. The analysis showed no significant main effect of the group factor \((F_{1, 19} = 3.19; \text{n.s.})\) or of the direction factor \((F_{1, 19} = 2.95; \text{n.s.})\). The interaction was also non significant \((F < 1)\).

Frequently, both controls and dyslexics corrected their initial undershooting with a second forward saccade (see Fig. 2b). In controls these corrective saccades were present in about 30% of cases with a similar frequency for rightward or leftward direction. The mean percentage of forward corrective saccades tended to be higher in dyslexics (about 40%). Inspection of the figure indicates that one control and one dyslexic (L.M.) showed a large percentage of corrections in the rightward direction.

An ANOVA showed no reliable effect of the group \((F_{1, 19} = 2.80; \text{n.s.})\) or direction factors \((F_{1, 19} = 1.16; \text{n.s.})\). The interaction was non significant \((F < 1)\).

When over-shooting a target, observers make a backward saccade (e.g., moving toward the left when tracking a target moving to the right; see Fig. 2c). In both controls and dyslexics these backward corrective saccades occurred in about 15% of cases, indicating no difference between the two groups. One dyslexic subject (C.S.) showed a high percentage of backward corrective saccades in the leftward direction.

An ANOVA showed no reliable effect of the group \((F_{1, 19} = 0.057; \text{n.s.})\) or direction factors \((F_{1, 19} = 1.04; \text{n.s.})\). The interaction was non significant \((F < 1)\).

3.5.1. Comments

In general, in these data there seems to be little indication of a specific deficit in the saccadic movements toward a target in the dyslexic group, confirming pre-
vious observations [3,4,21,22,35]. In particular, there is no indication of the presence of erratic eye movements, as originally observed by Pavlidis [26]; both controls and dyslexics made some forward saccades when initially undershooting the target or backward saccades when overshooting. Considering the homogeneity of the group in terms of reading disorder, it seems unlikely that a deficit in eye movement is a significant determinant of surface dyslexia.

However, this does not mean that all dyslexics’ eye movements are comparable to those of controls; in particular, L.M. made a very large number of corrections to compensate for systematic undershooting to rightward targets. The presence of subjects at variance within the dyslexic group has already been reported [35].

3.6. Reading task

3.6.1. Major parameters of eye movements

Fig. 3 presents the individual mean data separately for each parameter considered. An inspection of the figure reveals dramatic differences between the two groups: dyslexics showed more frequent (a) and smaller (b) saccades to the right, but there was no overlapping between the two groups. Regressions were slightly
more numerous in dyslexics (c) and of smaller amplitude (d); however, their percentage with respect to total eye movements was comparable to that of controls (e). Finally, fixation duration was longer, despite partial overlapping of individual data (f). D.I.'s values are indicated in the figure; note that in all cases her pattern was consistent with that of the younger dyslexics.

A set of univariate ANOVAs indicated that

- the number of rightward saccades per line was considerably greater in dyslexics (16.6) than in controls (7.4) \((F_{1,18} = 53.6; P < 0.0001; (a));
- the mean amplitude of rightward saccades was smaller in dyslexics (1.2°) than in controls (2.7°) \((F_{1,18} = 58.6; P < 0.0001; (b));
- regressive movements were more frequent in dyslexics \((F_{1,18} = 7.7; P < 0.01; (c)); however, there was no difference between the two groups when the percentage of regression on the total number of movements was considered (dyslexics: 18.9%; controls: 18.9%; \(F < 1; (e));
- the amplitude of regressions was smaller in dyslexics (0.9°) than in controls (1.6°) \((F_{1,18} = 29.5; P < 0.0001; (d));
- fixations were longer in dyslexics (290 ms) than in controls (234 ms; (f)).

3.6.2. Fixations as a function of text characteristics

The second type of analysis considered eye movements in relation to some characteristics of the reading material. In particular, the number of fixations per word made by each subject as a function of the length and frequency of each word was considered. Mean data of individual subjects are presented in Fig. 4; inspection of the figure indicates that dyslexics were considerably more sensitive to word length than controls; irrespective of word frequency, they needed about four fixations to read a 6–8 letter word, i.e., about twice those of controls.

An ANOVA with group as unpeated factor and word frequency and word length as repeated factors
was performed on the data. The dyslexics made a greater number of fixations per word than the controls (3.1 fixations per word vs 1.4; $F_{1,18}=32.29; P < 0.0001$); the word frequency effect fell short of significance ($F_{1,18}=3.63; P = 0.07$); word length greatly influenced the number of fixations ($F_{1,18}=26.29; P < 0.0001$). The interaction group x length was significant ($F_{1,18}=9.6; P < 0.01$). Analysis of simple effects shows that the effect of word length was significant in dyslexics ($F_{1,18}=33.83 P < 0.0001$) but not in the controls ($F_{1,18}=2.06; n.s.$).

A characteristic feature of expert readers is that when reading they neglect to fixate short words (most frequently, function words such as articles or prepositions [28]). We examined the number of short (1–3 letter) function words that were not fixated by the two groups. The comparison was based on a set of 31.2 function words for controls and of 30.0 for dyslexics ($t_{18}=4.05, P < 0.005$).

To show more clearly the relationship between number of fixations and word length, all available data of individual subjects for word lengths ranging from 1–12 letters are plotted in Fig. 5. Data include high- and low-frequency content words (i.e., nouns, adjectives and verbs) and high- and low-frequency function words (articles, prepositions, adverbs). An inspection of the figure indicates dramatic differences between the two groups. In dyslexics, the linear fitting shows the need for one additional fixation every 2-letter increase; a similar step occurs in controls only for 5-letter increases. However, the possible bias due to subjects’ different contribution (i.e., not all subjects produced reliable recordings for all word lengths) should be considered.

3.6.3. Comments

In general, the pattern of eye movements in functional reading was altered in dyslexics. They read the text through short and numerous saccades (more than a factor of 2 with respect to controls), followed by long fixations (about 20% longer than controls). The longer the word, the higher the number of saccades required, with about four fixations needed to decode a 6–8 letter word. In contrast, normal readers on average used less than two fixations for a 6–8 letter word. Unlike what is sometimes reported [26], the percentage of regressive eye movements was not higher in dyslexics (for a similar result see Ref. [1]).

The effect of word frequency on eye movements in expert readers is well established [29]. In an analytical study of English-speaking normal and dyslexic subjects, Hyönnä and Olson [14] found clear effects of both word frequency and length on parameters of fixation. In the present study, the effect of word frequency was small compared to that of word length. There may be different reasons for this. Firstly, to the extent to which surface dyslexics do not develop a sight vocabulary, but rely solely on grapheme-phoneme correspondence, it should be expected that word frequency will have no detectable effect on them. The expected effect
in controls may have been too small to be detected because of the size of our two samples\(^1\). Secondly, this outcome may at least in part be influenced by the regularity of the spelling-sound correspondences in Italian, which underscores the effect of word length \[16\].

\(^{1}\) A separate ANOVA on controls' data shows a reliable effect of word frequency \((F_{1,9} = 6.71, P < 0.05)\) with more fixations being made on less frequent words. The word length effect is also present \((F_{1,9} = 5.95, P < 0.05)\). There is no interaction between the two factors \((F_{1,9} = 1.37, \text{n.s.})\).

4. Discussion

The present work shows that children suffering from surface dyslexia have an altered pattern of eye movements in reading a text. In contrast, their ability to fixate steadily and to saccade toward a left or right non-linguistic stimuli appears essentially spared. These findings support the idea that the alteration of eye movements in surface dyslexia does not depend on oculomotor dysfunction per se but is secondary to a defect in the visual processing of linguistic material. In particular, the eye movement pattern in these children

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**Fig. 5.** Reading task. Number of fixations per word as a function of word length separately for controls (C) and dyslexics (D). Plotted values represent all available individual data independent of word frequency and word type (content, function). Experimental points were fitted by linear regression. Line equations and \(R^2\) are reported.
seems to reflect their difficulty in processing visual material into lexical information. In agreement with data in the literature [28], expert readers in the control group quickly scanned the text, picking up information with brief fixations generally centered around the mid-word followed by relatively long saccades towards the following word, often skipping short words such as function words. On the other hand, the dyslexics rarely skipped even very short words. They scanned the text through many and relatively long fixations pausing on different letters of the same word, suggesting a parsing of words into sub-units, as predicted by a grapheme-phoneme conversion mode of processing. Overall, the eye movement pattern in these children seems to reflect a failure in visual access to lexicon, i.e., the processing route that allows expert readers to rapidly convert a string of letters, like a visual gestalt, into a lexical item.

As stated in the Introduction, a number of authors have also favoured a linguistic rather than an oculomotor interpretation of dyslexia (for a review see Ref. [21]). However, in general there has been a tendency to consider the altered pattern of eye movements during reading simply as an expression of the delay in the development of reading achievement [14]. The critical finding for this view is that average differences between groups of dyslexics and controls vanish when they are matched for reading rather than chronological age [21]. In a general sense, the present findings are not incompatible with a delay interpretation. However, the developmental lag hypothesis cannot easily explain the dissociation in performance observed when measuring different reading parameters. This is very clear when comparing performance in comprehension against speed and accuracy; thus, several (although not all) dyslexics are impaired in reading speed but understand the meaning of a text. This dissociation is most evident in the case of our older subject D.I.. When reading lists of words, she was almost as slow as an 8-year old and accurate as a 9-year old. In the homophone comprehension test of her performance was that of an 11-year old; when her text comprehension was examined, she was within the normal range for her age (18 years). Overall, at least in languages with transparent morphology, it seems that a single value for reading age does not meaningfully describe reading performance since comprehension may be dissociated from speed and accuracy. In contrast, in studies of eye movements, reading comprehension is commonly used to establish reading age either alone [4] or with other parameters such as spelling and recognition [14].

Here, we propose that the characteristic pattern of eye movements observed in surface dyslexics specifically probes the type of processing of written material made by these subjects. This proposal seems to be a meaningful change in perspective. D.I.’s eye movements reflect the need for a fragmented analysis of written material and are in fact indistinguishable from those of the dyslexics 7–8 years younger, who read more slowly, with a larger number of errors and with lower comprehension.

A corollary of the hypothesis that pattern of eye movements marks type of reading process is that one should not expect eye movements to be impaired in the same way in all dyslexics. Subjects relying only on the grapheme-to-phoneme correspondence, such as the one examined in the present study, will present the above described pattern. However, one may expect that phonological dyslexics, who rely solely or predominantly on direct visual access to the lexicon, will not show a pattern reflecting fragmented reading. In brief, no systematic shortening of rightward saccades should be expected. Results relevant to this problem were reported by Olson and colleagues [23] in a study of individual reading style as related to pattern of eye movements during reading. These authors noted that some dyslexic subjects display few word-skipping forward movements and regressions between words; further, they tend to move steadily forward with more frequent within-word saccades. These subjects were defined as ‘plodders’ and appear quite similar (although generally less impaired) to the surface dyslexics of the present study. Consistently, these plodders tend to be low on a test of orthographic skill (and high in phonological spelling). At the other extreme, are ‘explorer’ subjects who have a different eye movement pattern. These subjects make more word-skipping movements and fewer intra-word and word-to-word progressive movements. They score higher in orthographic skill and lower in phonological spelling. These latter findings seem to suggest the pattern of eye movements that can characterise phonological dyslexia. Examination of a group of subjects on the basis of an extensive cognitive evaluation to determine the presence of phonological dyslexia will be necessary to assess this question conclusively. To date the rarity of Italian-speaking phonological dyslexics [31] has prevented us from carrying out this type of test.

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