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RAPID COMMUNICATION

Reading Words and Pseudowords: An Eye Movement Study of Developmental Dyslexia

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The pattern of eye movements during reading was studied in 12 developmental dyslexics and in 10 age-matched controls. According to standard reading batteries, dyslexics showed marked reading slowness and prevalently used the sublexical procedure in reading. Eye movements were recorded while they read lists of short and long words or pseudowords. In normal readers, saccade amplitude increased with word length without a concomitant change in the number of saccades; in contrast, the number of saccades increased for long pseudowords. In dyslexics, the eye movement pattern was different. The number of saccades depended on stimulus length for both words and pseudowords while saccade amplitude remained small and constant. The sequential scanning shown by dyslexics for both words and pseudowords appears consistent with the cognitive description of the reading disorder which indicates the preferential use of the sublexical print-to-sound correspondence rules.

Key Words: eye movements; dyslexia; reading; pseudoword.

Measuring eye movements is a potentially powerful way to study developmental reading deficits. However, interpreting findings requires in-depth knowledge of the subject's reading deficit. This analysis is typically neglected in most eye movement studies (e.g., Adler-Grinberg & Stark, 1978; Olson, Conners, & Rack, 1991). Cognitive studies show that dyslexics present two main qualitatively different performance patterns. Some subjects are impaired in reading new verbal material such as pseudowords (e.g., Castles & Coltheart, 1993; Snowling & Rack, 1991). In the absence of lexical correspondence, these pronounceable strings of letters must be read by using the grapheme–phoneme correspondence rules. Therefore, these subjects are specifically impaired in the use of the sublexical reading procedure (phonological dyslexia). Other subjects show a severe deficit in reading irregular words (such as ''yacht'') or in discriminating homophones (such as ''wait'' and ''weight''; Castles & Coltheart, 1993). The sublexical print-to-sound correspondence rules are not sufficient for reading these stimuli and reference to an orthographic lexicon is required. Therefore, these subjects are thought to have a deficit in the lexical reading procedure (surface dyslexia). Although widely adopted, this hypothesis has also re-

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ceived considerable criticism. Some authors have even questioned the specificity of the surface dyslexia symptoms (e.g., Stanovich, Siegel, & Gottardo, 1997; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996) and posited the predominance of the phonological deficit in generating the reading disorder (Snowling & Rack, 1991). Pure cases of both phonological and surface dyslexia (e.g., Castles & Coltheart, 1996) have been reported infrequently with most dyslexics showing a partially mixed pattern. Castles and Coltheart (1993) argued that the phonological-surface dichotomy may prove useful even though, in most cases, it expresses a relative, rather than an absolute, asymmetry. Within this framework, the present study focuses on the eye movement reading pattern of Italian dyslexics, characterized by the predominant use of the print-to-sound correspondence rules. In view of the above-mentioned controversy, we identify the participants of our study as sublexical readers to indicate their preferential procedure of reading, without committing ourselves to the definite diagnostic category of surface dyslexia.

As compared to English language context, defects in the lexical route in languages with regular grapheme–phoneme correspondence rules, such as Italian, require some further characterization of the reading pattern since there are no irregular words or homophones. It has been observed that in regular orthographies errors in reading are relatively rare and the most apparent symptom is reading slowness (Wimmer, 1993). This has been interpreted as due to the use of sequential sublexical reading (Zoccolotti, De Luca, Di Pace, Judica, Orlandi, & Spinelli, 1999). This idea is supported by the finding that vocal reaction times of Italian surface dyslexics depend on word length (Zoccolotti et al., 1999), an expected result in the case of sequential processing. Moreover, when we examined eye movement patterns during reading, these subjects showed numerous and very small rightward saccades; fixation duration was also longer (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999). Finally, the number of fixations varied with word length in dyslexics but not in controls. This eye movement pattern seems representative of the highly fragmented, sequential reading procedure adopted by these subjects.

Our previous findings were based on the examination of eye movements during the reading of a meaningful text. To further investigate the idea that small and numerous rightward saccades are associated with the predominant use of the sublexical reading procedure, we compared the dyslexics' eye movements in reading different length words and pseudowords to those of a group of age-matched control subjects.

The hypothesis was that the dyslexic subjects would show a similar parceled pattern of eye movements regardless of the lexical value of the letter string and that the control subjects' visual scanning would discriminate between words and pseudowords. Regarding the number of saccades, a length effect was expected with both words and pseudowords in dyslexics but only with pseudowords in control participants.

MATERIALS AND METHODS

Participants

The criteria for inclusion in the dyslexic sample were the following: marked reading delay on a standard reading test (see below), performance in the normal range (above 10th percentile = score 22) on Raven's Coloured Progressive Matrices, normal or corrected-to-normal visual acuity, and absence of severe refractive errors. The dyslexic sample included 12 participants. Mean performance on Raven's test was 29.3 (*SD* = 2.8). All participants but 1 were male. They were all enrolled in the middle school. Age ranged from 11 years and 9 months to 16 years and 6 months (Mean = 13.1; *SD* = 1.2 years). A control group of participants with normal reading ability was also tested. It included 10 participants (nine males) ranging in age from 11 years and 5 months to 14 years and 8 months (Mean = 12.4; *SD* = 1.0 years). All participants had at least 10/10 (range 10–11) mean binocular visual acuity.

Reading Assessment

Two standard reading evaluation instruments were used; one assessed reading level and the other further characterized the nature of the reading disorder.

Reading level was examined with a standard reading achievement test (MT Reading test; Cornoldi & Colpo, 1981). Two meaningful passages were presented. In the first, the participant had to read aloud (with a 4-min time limit); speed (time, in seconds, per syllable read) and accuracy (number of errors, adjusted for the amount of text read) were scored. A second passage was presented without a time limit; the participant 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. Performances are expressed in terms of *z* scores, indicating degree of deviation from the normative data.

In the dyslexic subgroup, the nature of the reading disorder was examined by means of the Developmental dyslexia and dysorthography battery (Sartori, Job, & Tressoldi, 1995). A screening subtest (*Graphemes*) required the participant to read aloud 21 single letters. Two subtests checked the reading of *Words and Pseudowords.* A list of 112 words was presented and the participant was required to read them aloud. A similar list of 48 pseudowords was presented. Number of errors and speed of reading were scored. Unlike English, Italian has very few homophonic words. Specific stimuli were used to approximate homophonic contrasts (same pronunciation with different graphic characteristics). In one subtest (*Comprehension of homophones*) the participant was required to choose the correct item from among four alternatives such as the following: *l'ago* é 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 than ''lago'' (''lake''). Twenty-four trials were given. The number of errors was computed. In the other subtest (*Discrimination of homophonic sentences*), the participant was 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 was required to indicate whether they were correct. Again, this task could not be solved by referring to a grapheme–phoneme conversion; visual-orthographic analysis of the stimuli was required. The number of errors was computed.

For all subtests, performances are expressed in terms of *z* scores, indicating degree of deviation from the normative data (Sartori et al., 1995).

Eye Movement Recordings

Apparatus and general procedure. Eye movements were recorded by means of an infrared pupil reflection system (AMTech ET4 Eye Tracking System). That allows measuring the movements of one eye both horizontally and vertically. The sampling rate was 500 Hz. The system has a maximum accuracy of five primes of arc. The participants sat on a chair. Their heads were kept immobile during recording by a headrest and a chin-rest. They 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 before each reading trial. The participant was requested to fixate a target (a little square) displayed in six different successive positions on the screen in a 3×2 matrix spanning 24.0° horizontally and 2.5° vertically. After fixation on the first square, the target disappeared and a new target appeared in the next position. The participant's task was to saccade each successive position. The reading task (see below) was performed immediately after calibration.

The portion of the trace contaminated by artifacts due to blinks was signaled by the computer and rejected. Artifacts due to occasional head movements were rejected. Only artifact-free recordings were used.

Stimuli and procedure. The stimuli consisted of lists of words or pseudowords. Each list contained 8 items, displayed in 2 rows of 4 each. Half of the word lists presented short (4–5 letters) and half long (8–10 letters) words. The same was true for the lists of pseudowords. There were 8 lists of words for a total of 64 words (32 short and 32 long). Similarly, there were 8 lists of pseudowords.

All words used were of high frequency according to a standard instrument (IBM Italia, 1989). Short and long pseudowords were generated from the word stimuli changing either one [e.g., ''parte (''part'') → parne''] or two letters [''funzione'' (''function'') → ''banzione''], respectively.

Stimuli were presented in Courier font on a white background. Mean character width was 0.5°. Lists were fully displayed on the screen without a time limit.

The participant's task was to read the lists silently. To check compliance with the task, four words

TABLE 1
Performance of Dyslexic and Control Subjects on the MT Battery

	Control subjects		Dyslexic subjects	
	Mean	*SD*	Mean	*SD*
Speed	0.45	0.8	−3.32	2.1
Accuracy	0.35	0.4	−2.80	1.7
Comprehension	0.19	0.6	−.68	0.7

Note. *Z* scores based on Italian normative data (Cornoldi & Colpo, 1981) are reported. Negative values indicate performances below the norm. *Z* scores were used because subjects were different ages (11–14 years) and norms vary with age.

were read by the experimenter after each trial and the reader was requested to indicate the two that were part of the list.

Analysis. Four parameters of eye movements in reading were considered: number of rightward saccades per item (either word or pseudoword), amplitude of rightward saccades (in degrees), number of regressions per item, and fixation duration (in milliseconds).

RESULTS

Reading Performance

Performances on the MT battery are presented in Table 1 for both dyslexic and control participants. The dyslexics' performance was severely impaired in both the speed and accuracy parameters, i.e., it was approximately 3 standard deviations below the normative values. Ability to understand the text was only mildly impaired. Mean *z* scores of control participants were near zero for all three parameters, as expected.

Examination of the reading defect is presented in Table 2. The ability to read

TABLE 2
Performance of Dyslexic Subjects on the Developmental Dyslexia and Dysorthography Battery

	Dyslexic subjects	
	Mean	*SD*
Graphemes (accuracy)	+0.22	0
Words (speed)	−5.67	4.7
Words (accuracy)	−3.19	2.7
Pseudowords (speed)	−4.60	5.3
Pseudowords (accuracy)	−2.81	1.9
Homophone comprehension	−1.47	1.0
Discrimination of homophonic sentences	−1.61	1.7

Note. *Z* scores based on normative reference data (Sartori et al., 1995) are reported. In all cases, negative values indicate performances below the norm.

graphemes was normal. Accuracy in word reading and, to a greater extent, speed, was dramatically affected. Values of the pseudowords were similar to those of the words indicating a severe deficit that was more marked for speed. Performance was poor in detecting errors in pseudohomophones for both the *Comprehension of homophones* and the *Discrimination of homophonic sentences* subtests. Note that the range of possible performances in these two latter tests is relatively small; chance performance was at z values of ca. -2.5, depending on participant's age.

Comments

The reading impairment shown by the dyslexic group was characterized mostly by slowness and errors in reading. This was true for both meaningful texts (Table 1) and lists of words (Table 2). Comprehension was largely spared. This pattern confirms previous results obtained in Italian dyslexics (Zoccolotti et al., 1999), indicating that, despite errors and slowness, the text can be comprehended if enough reading time is given to the participant.

Analysis of the dyslexics' reading deficits indicated a dramatic deficit in both speed and accuracy in reading words; reading of pseudowords was similarly affected. Consequently, no indication of a selective deficit for this latter material was found. There was also a deficit in solving pseudohomophonic contrasts. Overall, this pattern points to the prevalent use of the sublexical grapheme-to-phoneme procedure.

Eye Movements

Number of rightward saccades. The mean number of saccades per item was submitted to an ANOVA with group (control/dyslexic) as nonrepeated factor and stimulus type (words/pseudowords) and stimulus length (short/long) as repeated factors. As stated above, the hypothesis of the study was that a length effect would be found in dyslexics for both words and pseudowords but only for pseudowords in control participants; this would be expressed as a second-order interaction between group, stimulus type, and stimulus length. This proved significant [$F(1, 20) = 6.86$, $p < .05$]. The relevant means of this latter interaction are presented in Fig. 1.

The control participants read short words and pseudowords with a similar number of saccades; in contrast, they showed more saccades for long pseudowords than for words ($p < .05$, Tukey HSD test). The dyslexic participants showed the opposite pattern, that is, they displayed more saccades in reading short pseudowords than words ($p < .05$) but no difference between long pseudowords and words. Examining the means in terms of the length effect in the same type of stimuli, both groups showed more saccades for long than for short pseudowords (ca. about a 50% increase; in both cases $p < .01$). The dyslexics, but not the controls, showed more saccades also for long words ($p < .01$).

The analysis also showed that all main effects were significant (at least $p < .005$), indicating more numerous saccades in dyslexics than in controls in reading pseudowords than words and for long rather than for short stimuli. Finally, the interaction between group and stimulus length proved significant [$F(1, 20) = 21.9$, $p < .05$]. No other interaction was significant.

Saccade amplitude. A similar analysis was made on mean saccade amplitude. In this case, we expected that saccade amplitude would be modulated by the length of the item only in controls and only in the case of words. The predicted second-order interaction between group, stimulus type, and stimulus length was significant [$F(1, 20) = 5.2$, $p < .05$]. The relevant means of this latter interaction are presented in Fig. 2.

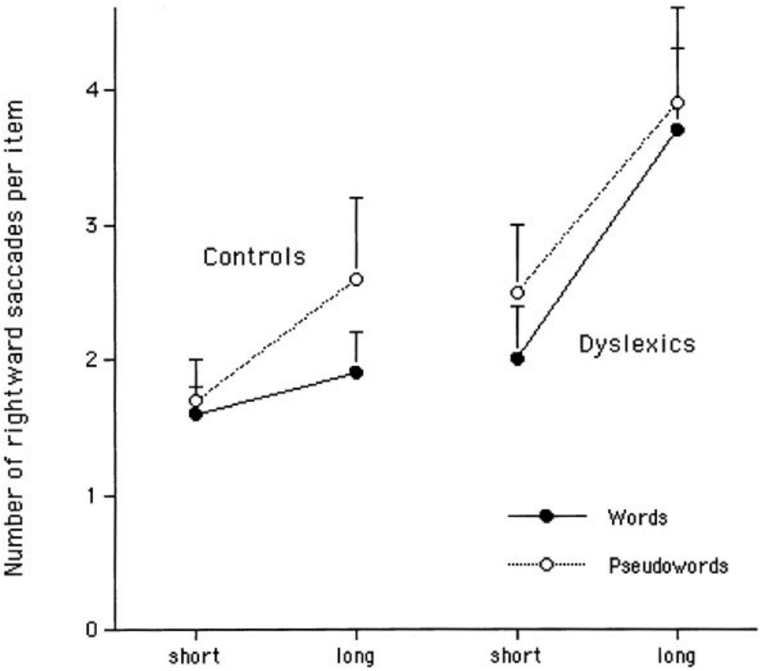

FIG. 1. Mean number of rightward saccades for dyslexic and control subjects as a function of type (word/pseudoword) and length (short/long) of the stimulus. Bars indicate 95% confidence intervals.

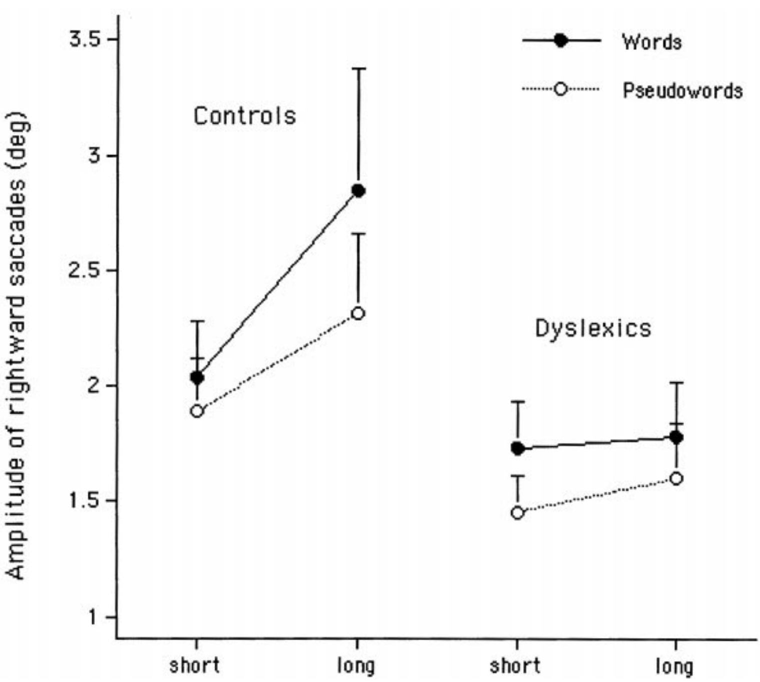

FIG. 2. Mean saccade amplitude for dyslexic and control subjects as a function of type (word/pseudoword) and length (short/long) of the stimulus. Bars indicate 95% confidence intervals.

The control participants showed no amplitude difference between short words and pseudowords; in contrast, they displayed larger saccades for long words than for pseudowords ($p < .01$). The dyslexic participants showed no difference between words and pseudowords for either short or long stimuli. In terms of the length effect, the controls showed a strong difference between short and long words (ca. 40% increase; $p < .001$) and a smaller but significant difference between short and long pseudowords (ca. 20% increase; $p < .05$). In contrast, no length effect was present in dyslexics for either type of stimuli.

All main effects were significant (at least $p < .001$). Saccades were shorter in dyslexics than in controls, in reading pseudowords rather than words, and for short rather than long stimuli. The first-order interaction between group and stimulus length [$F(1, 20) = 14.3$, $p < .001$] was significant. No other interaction was significant.

Number of regressive movements. Regressions were rare, accounting for about 9% of the total number of eye movements in the control participants and 14% in the dyslexic participants.

An ANOVA confirmed the presence of a second order interaction among group, stimulus length, and stimulus type factors [$F(1, 20) = 7.6$, $p < .05$]. The relevant means are presented in figure 3.

The general pattern of results was similar to that of the number of the forward saccades, but on a smaller scale. The controls showed no difference for short stimuli and they tended to make more regressions for long pseudowords than for long words ($p = .06$). The dyslexics showed the opposite pattern, i.e., more regressions for short pseudowords than for words ($p < .05$) and no difference for long stimuli. In terms of the length effect, this was absent in the controls and limited to words in the dyslexics ($p < .01$).

Further, the analysis indicated more regressions per word for dyslexics than for

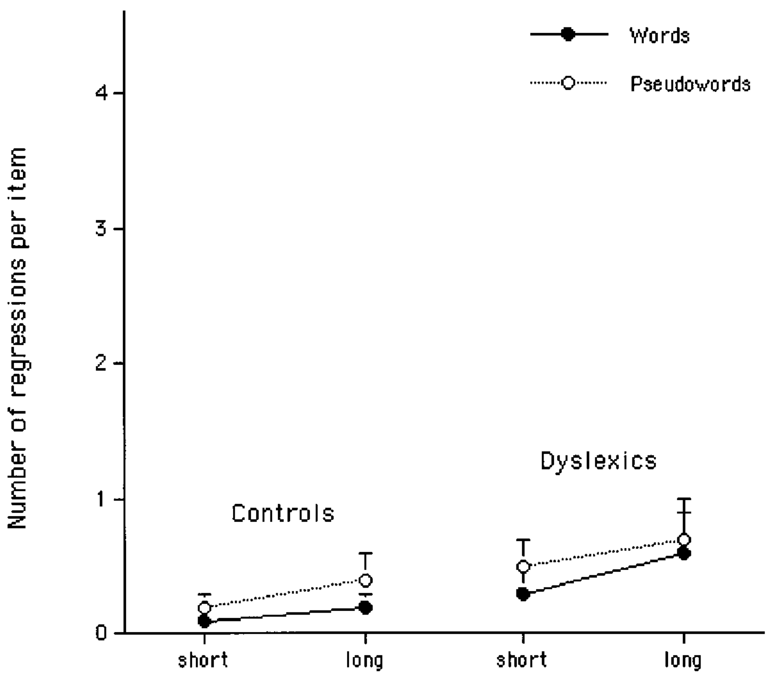

FIG. 3. Mean number of regressive saccades for dyslexic and control subjects as a function of type (word/pseudoword) and length (short/long) of the stimulus. Bars indicate 95% confidence intervals.

controls, for pseudowords than for words, and for long rather than for short stimuli (all *p*s at least $<.01$).

Fixation duration. The ANOVA indicated a main effect for the stimulus type factor [$F(1, 20) = 22.1$, $p < .001$], indicating longer fixation duration for pseudowords (263 ms) than for words (240 ms). The main effect of group approached significance [$F(1, 20) = 3.84$, $p = .06$], indicating longer fixations for dyslexics (270 ms) than for controls (234 ms). No interaction was significant.

DISCUSSION

Proficient readers scan written texts flexibly, adjusting their forward saccades to word length. In the case of long words, saccades are larger than those for short words; however, their number remains about the same. This behavior indicates the advantage of processing words. When strings have no lexical entry (pseudowords), the number of saccades increases with stimulus length and only a small increase in amplitude is observed. In contrast, dyslexics' reading indicates a marked length effect independent of the lexical value of the stimulus: For both words and pseudowords, the number of saccades increases with stimulus length while saccade amplitude remains small and constant. The pattern for regressive movements generally parallels that of forward saccades.

Fixation duration (i.e., the time during which the eyes focus on the target to pick up information) depends on stimulus type; it is about 20 ms shorter when the target is a meaningful word rather than a pseudoword with the same number of letters. Fixation duration tends to be longer (about 40 ms) in dyslexics than in controls. This finding supports the stronger effect observed in our previous study (about 60 ms; De Luca et al., 1999). Taking the results of the two studies together, it seems that differences between controls and dyslexics are marked regarding the way their eyes scan the stimulus and somewhat less robust in terms of time of processing.

The present data on eye movements are consistent with the cognitive description of the reading disorder, indicating a prevalent reliance on the sublexical print-to-sound reading procedure. Dyslexics' eye movements were characterized by the sequential analysis of relatively small word subunits. Indeed, 8- to 10-letter words were fragmented into three or four segments. Parceled eye movement scanning supports the notion that these readers prevalently use the sublexical mode of processing, a procedure evident in the controls only when they read long pseudowords.

Summarizing the pattern of data, it appears that dyslexics read words in the same way controls read pseudowords; in other words, they adopt a sublexical grapheme-to-phoneme procedure regardless of the lexical value of the target. However, this conclusion must be corrected by two observations. First, the way dyslexics scan short stimuli discriminates between words and pseudowords. This finding holds for number and amplitude of rightward saccades as well as for number of regressions and implies a certain degree of sighting vocabulary even though limited to four- to five-letter words. Note that the way controls scan short stimuli is similar for words and pseudowords, indicating that reading these stimuli may be particularly easy for good readers.

Second, when dealing with long stimuli, the dyslexics' processing of words (as well as pseudowords) is more parceled than that of the controls' reading of pseudowords, i.e., the number of forward saccades is ca. 30% higher and saccade amplitude is ca. 40% smaller in the dyslexics than in the controls. This finding adds to the frequent observation in cognitive analysis of surface-type dyslexic symptoms; that is, these subjects read pseudowords more slowly and with more errors than normal subjects (e.g., Wimmer, 1996; Job, Sartori, Masterton, & Coltheart, 1983). A similar observation also emerged in the present behavioral data (see Table 2). Therefore, while an impairment of the lexical procedure may be prominent, the sublexical procedure of reading itself may not be entirely spared in these subjects. This is consistent with the proposal by Coltheart and colleagues (e.g., Castles & Coltheart, 1993) that deficits in either lexical or sublexical procedures are best expressed in terms of the relative efficiency of the two procedures rather than in terms of the absolute lack of one or the other. Thus, in the dyslexics both procedures would be damaged, but one more than the other. Another alternative is that dyslexia is the reading manifestation of an underlying visual deficit not limited to linguistic stimuli. Although basic visual functioning was within normal limits, dyslexics may be specifically impaired in the visual processing of small, closely spaced stimuli, characteristically required in reading. This impairment would affect both reading procedures, but would be more detrimental for one of the two. Further research is needed to test this hypothesis.

Alteration of the eye movement pattern during reading in dyslexics has been interpreted in various ways. One hypothesis is that eye movement derangement is the cause of dyslexia (e.g., Pavlidis, 1981). On the contrary, several studies failed to confirm this hypothesis and posited that the perturbation of eye movements is a manifestation of a linguistic deficit (e.g., Olson, Conners, & Rack, 1991; Hyönä & Olson, 1995). However, these latter studies neglected the characteristics of their subjects' reading disorder and, thus, failed to specify the effect of such a deficit on the perturbation of the eye movement pattern. The present research indicates that the pattern of eye movements reflects the characteristic sublexical mode of processing written information. This mode is the slow processing by sequential grapheme–phoneme conversion of small pieces of a word in the absence of a more rapid global analysis.

REFERENCES

Adler-Grinberg, D., & Stark, L. (1978). Eye movements, scanpaths, and dyslexia. *American Journal of Optometry & Physiological Optics,* **55,** 557–570.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition,* **47,** 149–180.

Castles, A., & Coltheart, M. (1996). Cognitive correlates of developmental surface dyslexia: A single case study. *Cognitive Neuropsychology,* **13,** 25–50.

Cornoldi, C., & Colpo, G. (1981). *La verifica dell'apprendimento della lettura: Guida all'uso.* Firenze: Organizzazioni Speciali.

De Luca, M., Di Pace, E., Judica, A., Spinelli, D., & Zoccolotti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia,* **37,** 1407–1420.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* **21,** 1430–1440.

IBM Italia. (1989). *VELI, Vocabolario Elettronico della Lingua Italiana.* Milano: IBM.

Job, R., Sartori, G., Masterton, J., & Coltheart, M. (1983). Developmental surface dyslexia in Italian. In R. N. Malatesha & H. Whitaker (Eds.), *Dyslexia: A global issue* (pp. 133–141). The Hague: Martinus Njihoff.

Manis, F. R., Seidenberg, M. S., Doi, L. M., McBride-Chang, C., & Petersen, A. (1996). On the basis of two sub-types of developmental dyslexia. *Cognition,* **58,** 157–195.

Olson, R. K., Conners, F., & Rack, J. (1991). Eye movements in dyslexics and normal readers. In J. F. Stein (Ed.), *Vision and visual dyslexia.* Houndmills: Macmillan.

Pavlidis, G. T. (1981). Do eye movements hold the key to dyslexia? *Neuropsychologia,* **19,** 57–64.

Sartori, G., Job, R., & Tressoldi, P. E. (1995). *Batteria per la valutazione della dislessia e della disortografia evolutiva.* Firenze: Organizzazioni Speciali.

Snowling, M., & Rack, J. (1991). Dyslexia: Defects in the development of grapheme–phoneme correspondence. In J. F. Stein (Ed.), *Vision and visual dyslexia.* Houndmills: Macmillan.

Stanovich, K. E., Siegel, L. S., & Gottardo, A. (1997). Converging evidence for phonological and surface subtypes of reading disability. *Journal of Educational Psychology,* **89,** 114–127.

Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics,* **14,** 1–33.

Wimmer, H. (1996). The nonword reading deficit in developmental dyslexia: Evidence from children learning to read German. *Journal of Experimental Child Psychology,* **61,** 80–90.

Zoccolotti, P., De Luca, M., Di Pace, E., Judica, A., Orlandi, M., & Spinelli, D. (1999). Markers of developmental surface dyslexia in a language (Italian) with high grapheme–phoneme correspondence. *Applied Psycholinguistics,* **20,** 191–216.