Journal of Experimental Psychology:
Learning, Memory, and Cognition
1995, Vol. 21, No. 6, 1430-1440

Eye Fixation Patterns Among Dyslexic and Normal Readers: Effects of Word Length and Word Frequency

Jukka Hyönä
University of Turku

Richard K. Olson
University of Colorado at Boulder

Eye fixation patterns of 21 dyslexic and 21 younger, nondyslexic readers were compared when they read aloud 2 texts. The study examined whether word-frequency and word-length effects previously found for skilled adult readers would generalize equally to younger dyslexic and nondyslexic readers. Significantly longer gaze durations and reinspection times were found for low-frequency and long words than for high-frequency and short words. The effects also showed up in the number of fixations on the target words. The effects did not differ significantly for the 2 experimental groups. The results run counter to the oculomotor dysfunction hypothesis of dyslexia. Instead, they support the view that both dyslexic and nondyslexic readers' eye fixation patterns reflect their difficulties in successfully identifying words in a text.

Eye behavior during reading has interested psychologists since the early days of experimental psychology (see Venezky, 1993). As Rayner (1978) pointed out, psychologists are now in a new era of eye movement research, which has been predominantly influenced by cognitive psychology. Thus, during the last two decades there has been an increased interest in the study of eye movements in reading from the standpoint that readers' eye movement patterns reflect ongoing cognitive processes in a moment-to-moment fashion. This approach has been very fruitful, and there is now ample evidence that eye fixation patterns indeed reflect several perceptual and language processes that are carried out during reading (for a review, see Rayner & Pollatsek, 1989).

Quite apart, and independent, from this cognitive approach to eye movements in nondyslexic readers, there has been an enduring interest in research on reading disabled or dyslexic children in eye behavior per se, not as an index of cognitive processing. It is somewhat surprising that the cognitive and dyslexia lines of research have not really met each other. Cognitive psychologists using eye movements to study perceptual and language factors in reading have primarily focused on skilled reading, and very few studies have been conducted on developmental aspects of reading ability. However, researchers who have been interested in the relationship between eye movements and dyslexia have been keenly searching for signs of oculomotor dysfunctions among people with dyslexia. In this study, we tried to tie these two lines of research together by examining dyslexic readers' eye movements from a cognitive point of view. Before presenting our study, we give a brief summary of the eye movement studies conducted on dyslexia, followed by a description of some cognitive influences on reading eye movements that have been found in nondyslexic adult readers. Then we describe our study comparing these cognitive influences in dyslexic and normal children.

It has been known for some time that when dyslexic readers read material that is appropriate for nondyslexic readers of the same age, dyslexic readers' eye movements differ from those of nondyslexic readers in that they make longer fixations, shorter saccades, and proportionally more regressive (right to left) eye movements (e.g., Griffin, Walton, & Ives, 1974; Heiman & Ross, 1974; Rubino & Minden, 1973). These findings, together with other evidence, have led some researchers to suspect that dyslexia may be caused by abnormal eye movements, which in turn are assumed to be caused by some sort of visual or attentional deficit or oculomotor dysfunction (e.g., Biscaldi, Fischer, & Aiple, 1994; Eden, Stein, Wood, & Wood, 1994; Pavlidis, 1981, 1983). However, the observation that the reading eye movements of people with dyslexia differ from those of their age-matched peers is totally uninformative with respect to the causal influence of eye movements on dyslexia: Abnormal eye movements in reading may be caused by dyslexic readers' difficulties in decoding printed words (Rayner, 1985). Thus, researchers have been looking for other corroborating evidence. A demonstration that the eye movements of people with dyslexia are abnormal in nonreading tasks would be evidence favoring the oculomotor dysfunction hypothesis.

Most studies that have compared nonreading eye movements among dyslexic and nondyslexic readers have not been particularly favorable to the oculomotor dysfunction hypothesis. Of the few studies that did find significant differences between dyslexic and nondyslexic readers were those by Pavlidis (1981, 1983), who found that in a simple light-tracking

---

Jukka Hyönä, Experimental Psychology Laboratory, University of Turku, Turku, Finland; Richard K. Olson, Department of Psychology, University of Colorado at Boulder.

This work was supported in part by grants from the National Institutes of Health (HD-11681, HD-27802, and RO1 HD-22223). Jukka Hyönä's visit to Boulder was financially supported by the Academy of Finland and the University of Turku. Co-investigators on the Colorado Reading Project are John DeFries, David Fulker, Richard K. Olson, Bruce Pennington, and Shelly Smith. The contributions of staff members of the many Colorado school districts that participated in our research, and of the twins and their families, are gratefully acknowledged. We are grateful to Helen Forsberg for her help in the data analysis.

Correspondence concerning this article should be addressed to Jukka Hyönä, University of Turku, Experimental Psychology Laboratory, Lemminkäisenk 14-18 B, FIN-20520 Turku, Finland. Electronic mail may be sent via Internet to hyona@sara.utu.fi.

task his participants with dyslexia made significantly more saccades, had proportionately more regressive saccades, and experienced difficulties in staying fixated on the stimuli, as reflected in shorter first-fixation durations. For example, the group with dyslexia made 10 times as many regressive saccades compared with an age-matched group without dyslexia, and there was no overlap in the group distributions. However, most attempts to replicate Pavlidis's findings have been unsuccessful (Biscaldi et al., 1994; Black, Collins, DeRoach, & Zubrick, 1984; Brown et al., 1983; Fields, Wright, & Newman, 1993; Olson, Kliegl, & Davidson, 1983; Stanley, Smith, & Howell, 1983).

There are two studies that did find evidence that only partially accorded with Pavlidis's (1981, 1983) findings in a similar tracking task. Martos and Vila (1990) reported a higher number of saccades and a higher proportion of regressions for their oldest (11–12 years of age) group with dyslexia, which comprised 10 participants, although, unlike Pavlidis's results, the group distributions did overlap. A group of younger participants with dyslexia did not reliably differ from nondyslexic participants. Fischer, Biscaldi, and Otto (1993) found in their research that a subgroup of 4 adults with dyslexia made more saccades of smaller size together with shorter fixation durations in the Pavlidis task, but they did not make more regressions. However, in another study, Biscaldi et al. (1994) found that a subgroup of 6 young participants with dyslexia made fewer saccades of longer amplitude in the same task. In sum, there is little convincing evidence that people with dyslexia exhibit qualitatively distinct eye movement patterns in a sequential tracking task.

Other comparisons of dyslexic and nondyslexic groups used to support the oculomotor dysfunction hypothesis have examined additional eye movement parameters including smooth pursuit (Bogacz, Mendilaharsu, & Mendilaharsu, 1974; Eden et al., 1994), vergence eye movements (Eden et al., 1994), eye dominance (Stein & Fowler, 1985), instability of fixation (Raymond, Ogden, Fagan, & Kaplan, 1988), and very rapid "express" saccades (Fischer & Weber, 1990). These investigators have found differences between some dyslexic and nondyslexic comparison groups. It is not clear, however, how the observed eye movement differences would influence reading (e.g., smooth-pursuit and express saccades are not observed in reading; for an example of the absence of express saccades, see Inhoff, Topolski, Vitu, & O'Regan, 1993). On the basis of this type of finding, some researchers in the optometry community (Cohen, 1988) advocate the training of eye movements as an appropriate remedial approach to dyslexia. However, an extensive review of earlier eye movement training research showed no unique benefits for dyslexic readers (Taylor, 1965; for a more recent study, see Kavale & Mattson, 1983).

In Olson's research,[1] the eye movements of people with dyslexia have been compared with those of readers without dyslexia in another nonreading task, visual search (Olson, Conners, & Rack, 1991; Olson & Forsberg, 1993; Olson, Rack, & Conners, 1991). The task required participants to search for a pair of target symbols (e.g.,]\) in a background of distractor symbols (e.g., *]\{]:\/+?]\. . .). This task was chosen to include symbol patterns that were similar in spatial frequency and complexity to letter strings in text. Another unique aspect of this study was the use of a reading-level-match comparison wherein a group of older participants ($n = 101$; mean age = 15 years) with dyslexia was carefully matched on level of word recognition to a group of younger readers ($n = 101$; mean age = 10 years) without dyslexia. Thus, any group differences in eye movements on the visual search task would not be caused by differences in reading level. Although there was substantial within-group variation for which analyses of data from identical and fraternal twins indicated significant genetic influence, there were no significant differences between the dyslexic and nondyslexic groups in average saccade length or in the proportion of regressive eye movements. The sample was large enough to detect any important group difference in eye movements in this visual search task.

The reading-level-match comparison has also been used to address the question of whether dyslexic readers' abnormal eye movements in reading are a causal factor in dyslexia or are caused by problems in word decoding. Olson, Conners, and Rack (1991) compared the reading eye movements of 72 matched pairs of younger nondyslexic and older dyslexic children equated on level of word recognition. Again, there was substantial within-group variability that was partly linked to genetic factors, but there were no significant group differences in eye movements. The results indicated that dyslexic readers' frequently reported abnormal eye movements are a consequence rather than a cause of their reading difficulty.

Although Olson and colleagues have found no differences in the fundamental and traditional parameters of saccade length and proportion of regressions in reading-level-match comparisons, there has been no previous examination of possible dyslexic–nondyslexic reader differences in eye movement behavior in relation to the cognitive processing demands of specific words in the text. There is now ample evidence indicating that experienced readers' eyes are governed through the text by the ongoing word recognition and comprehension processes (for further details, see Rayner & Pollatsek, 1989). One of the basic findings in the recent eye movement literature is the so-called word-frequency effect (Henderson & Ferreira, 1990, 1993; Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986; Raney & Rayner, 1995; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Underwood, Hubbard & Wilkinson, 1990). Words that are relatively low in frequency receive longer fixations during reading than do high-frequency words. The effect is manifested in a greater probability of making a refixation on a word and sometimes also in a longer first fixation on a word. In other words, more processing needs to be done to identify a less familiar word than a highly familiar word. Similarly, longer words receive longer inspection times than do shorter words (Just & Carpenter, 1980; Rayner & McConkie, 1976), mainly because of long words attracting a refixation on them (Kliegl, Olson, & Davidson, 1983; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989). However, short words are left unfixated (i.e., they are skipped) more often than are long words (Rayner &

---

[1] A major focus of the project is on the genetic and environmental etiology of dyslexia. Therefore, the participants in this study were all either identical or fraternal twins.

McConkie, 1976). The word-length effect can be ascribed to acuity limitations of the visual system: Long words extend beyond the fovea where the acuity is greatest, thus increasing the need for making a fixation and even a refixation on a word. For example, Hyönä, Niemi, and Underwood (1989) showed that among skilled readers words that were from 10 to 16 characters long regularly attracted a refixation on them.

Most models of eye guidance ascribe ongoing cognitive processes a leading role in governing eye fixations in reading (see Rayner & Pollatsek, 1989). It should be noted, however, that there does not exist a total consensus on the issue, as there are researchers who maintain that low-level oculomotor factors are the major contributor in guiding readers' eyes. The most influential challenger has been O'Regan's (1992) strategy–tactics theory. O'Regan's theory stresses the importance of the fixation's landing position in words in determining fixation durations and refixation probabilities. The theory ascribes cognitive factors only a secondary role.

In this study, we examined whether word-frequency and word-length effects would generalize equally to dyslexic and nondyslexic children. In the study, we compared a group of children with dyslexia, who read clearly (at least 2 *SD*s) below the local age norms, to a younger group of nondyslexic readers whose reading performance was at or above their age norms. The two groups were not matched on the level of isolated word recognition, but a somewhat lower level of word recognition was allowed for the dyslexic group so that we could include a larger sample and have greater statistical power to detect any important group differences in cognitive influences on eye movements. One possibility to reconcile the highly inconsistent results with respect to a possible oculomotor deficit in dyslexia is to argue that it may be restricted to more serious dyslexics only. Our group comparison was intended to reflect this argument.

If eye movements reflect dyslexic readers' problems with print (as they do among skilled adult readers), eye fixation patterns on words that are difficult to decode (long and low-frequency words) should differ from those coinciding with easily recognizable words (short and high-frequency words). Because our dyslexia group's word decoding skills were somewhat below the level of the younger nondyslexia comparison group, it may also be predicted that word length and word frequency might exert a more pronounced effect for those with dyslexia. If, however, variation in the relative ease of word recognition is not reflected in dyslexic eye movement patterns, the hypothesis is supported that eye behavior of readers with dyslexia is dysfunctional or "erratic" in the sense that it is not governed by the ongoing reading process. This latter prediction is quite extreme and perhaps also quite implausible, because there is no obvious reason to believe that word recognition processes among readers with dyslexia would not at all be influenced by cognitive processes. A more reasonable oculomotor dysfunction hypothesis would claim that superimposed on the cognitive influences there are signs of oculomotor dysfunctioning as reflected in a greater number of fixations in general, regressive fixations in particular, and/or in shorter fixation durations.

Table 1
Characteristics of the Participants in the Dyslexia and Control Groups

Characteristic	Group	
	Dyslexia	Control
Age (years)	14.4	10.5
Range	12.1–16.6	8.6–12.2
PIAT score		
Word recognition		
Raw	107	127
z	−2.51	0.60
Comprehension		
Raw	91	114
z	−1.77	0.39
Spelling		
Raw	85	112
z	−1.49	0.27
IQ		
Total	96.2	115.0
Verbal	92.3	117.0
Performance	101.7	109.2

Note. PIAT = Peabody Individual Achievement Test.

Method

Participants

Twenty-one children with dyslexia and 21 controls who participated in the Colorado Reading Project were chosen for the study.[2] Inclusionary criteria for participants in both groups were: (a) a score of at least 85 on the Wechsler (1974) Verbal or Performance subscales, (b) no evidence of neurological problems (such as seizures), (c) no uncorrected visual acuity or auditory deficits, (d) exposure to adequate instruction, (e) no serious economic problems, and (f) English as the primary language spoken in the home. Children were from different parts of the state of Colorado, excluding the Denver inner city.

All dyslexic participants were reading at least 2 *SD*s below the mean for the population in the sampling area, as assessed by the word recognition subtest of the Peabody Individual Achievement Test (PIAT; Dunn & Markwardt, 1970), although all nondyslexic participants had at least an average reading score. The age ranges did not overlap between the two groups: The oldest control child was the same age as the youngest dyslexic child. Using the above criteria, we wished to create a comparison, where children with a clear word recognition deficit were compared with younger readers of at least average reading ability. Some characteristics of the dyslexic and control children's reading performance are given in Table 1. Despite being, on the average, 4 years older than the controls, the group with dyslexia lagged behind the normal group in word recognition, $F(1, 40) = 18.46, p = .0001$; spelling, $F(1, 40) = 85.37, p < .0001$; and reading comprehension, $F(1, 37) = 72.59, p < .0001$, as measured by the PIAT test. Children with dyslexia had a clearly lower verbal IQ, whereas their performance IQs were almost comparable (see Table 1).

Apparatus

Eye movements were recorded using a Model 1996 eye tracker (Applied Science Laboratories, Bedford, MA). This video-based

---

[2] A major focus of the project is on the genetic and environmental etiology of dyslexia. Therefore, the participants in this study were all either identical or fraternal twins.

system compares the relative positions of the participant's pupil and corneal reflection to compute eye position at a sampling rate of 60 Hz. Fixations were calibrated to locations in character position and line number on the computer display. The estimated position accuracy was within ±1 character space on 90% of fixations (see Kliegl & Olson, 1981, for further details on the procedure for calibrating and mapping fixations to character and line positions).

Materials

All participants read the same two 8th-grade-level texts from the Spache Diagnostic Reading Scales (Spache, 1963). These texts were selected to be at a higher difficulty level than most participants' level of word recognition so that some reading errors would be generated (the grade-equivalent score in the PIAT word recognition test was 5.8 for the dyslexic and 7.7 for the nondyslexic participants). One story, of 212 words, dealt with reading and reading strategies and the other, of 206 words, was about an episode in American history. Up to 11 double-spaced lines were displayed on the computer screen. Each line contained up to 60 character spaces at a maximum 20° of visual angle.

From the two texts, words were identified that were of variable length and frequency. To allow for an orthogonal comparison of word length and word frequency, a set of high-, medium-, and low-frequency words was chosen for each of the following word lengths: short (5–6 letters), medium (7–8 letters), and long (9–11 letters). If possible, 10 words of each kind were identified in the stimulus texts. The conditions that contained less than 10 words were high-frequency/long ($n = 4$), high-frequency/medium ($n = 9$), low-frequency/short ($n = 8$), and low-frequency/medium ($n = 9$). The word frequencies were taken from the American Heritage Intermediate corpus, which is sampled to represent reading material that school-aged children in Grades 3–9 are exposed to in the United States (Carroll, Davies, & Richman, 1971). For the short words, the average estimated word frequencies (per million tokens) were 329, 51, and 3, for high-, medium-, and low-frequency words, respectively; for the medium-length words, the respective means were 298, 53, and 10; and for the long words, 293, 39, and 2, respectively.

Procedure

The eye tracker was calibrated by using nine fixation points extending the visual field where the text was presented. Participants were then asked to read aloud the first text. If they encountered words that they could not recognize immediately, participants were instructed to try to sound it out or guess the identity of the word. A few questions about the text were asked orally immediately after the text was read. The same procedure was repeated for the second text.

Results

Durations and frequencies of fixations landing on the target words were analyzed. Fixations landing on the space preceding the target word were also included in the measures, whereas fixations falling on the space to the right of word were excluded. In most cases, target words were fixated at least once. Skipped words were not included in the analyses except for the number of first-pass fixations.

Two stages of word processing were delineated: first-pass reading and second-pass reading of the target words. The first-pass reading consisted of all the fixations landing on a word before moving away from it to either a previous or a subsequent word. The second-pass reading entailed all the reinspections of a word executed after the first-pass reading. In the following, data are presented separately for first-pass reading and reinspections. Moreover, data on the duration of initial fixation are also reported. Analyses of variance were performed on the data using both subjects (F_1) and items (F_2) as cases. In the subject analysis, there were two within-subject variables: word frequency (high, medium, or low) and word length (short, medium, or long), and reading skill as the between-subject variable. In the item analysis, all variables were between-item variables. The statistical analyses were performed using the BMDP Statistical Software (Dixon, 1990). A Geisser–Greenhouse adjustment was made to the significance level whenever needed. Analyses of contrasts between different levels of a within-subject variable are computed by BMDP in a manner similar to new two-way t-tests are computed. In the item analyses, the contrasts were tested using Tukey's honestly significant difference test.

First-Fixation Duration

We first report data on the duration of the initial fixation on the target words, regardless of how many fixations were made after the first one (see Table 2). For the duration of initial fixation, word length did not produce a significant main effect (both Fs < 2). The means were 311, 308, and 323 ms, for the long, medium-length, and short words, respectively. However, the main effect of word frequency was highly significant, $F_1(2, 80) = 46.24$, $MSE = 3{,}763$, $p < .0001$; $F_2(2, 140) = 22.17$, $MSE = 3{,}062$, $p < .0001$. First-fixation durations were 284, 303, and 355 ms, for the high-, medium-, and low-frequency words, respectively. All pairwise contrasts were also significant by subjects (all ps $< .01$), whereas in the item analysis, low-frequency words differed from medium- and high-frequency words ($p < .01$).

The Frequency × Length interaction reached significance, $F_1(4, 160) = 8.94$, $MSE = 4{,}378$, $p < .0001$; $F_2(4, 140) = 5.19$, $MSE = 3{,}062$, $p < .001$. An analysis of simple effects showed that for medium-length words there was no word-frequency effect (both Fs < 1; the means were 304, 304, and 317 ms, for the high-, medium- and low-frequency words, respectively). However, this was clearly the case for short words, $F_1(2, 80) =$

Table 2
First-Fixation Duration (in Milliseconds) as a Function of Word Frequency and Word Length in Dyslexia and Control Groups

Word length	Word frequency			
	High	Medium	Low	*M*
	Dyslexia group			
Short	267	303	396	322
Medium	305	322	316	314
Long	273	289	355	306
M	282	305	356	314
	Control group			
Short	267	303	402	324
Medium	303	286	318	302
Long	287	315	346	316
M	286	301	355	314

40.00, $MSE = 4,892$, $p < .0001$; $F_2(2, 140) = 27.18$, $MSE = 3,062$, $p < .0001$ (the means were 267, 303, and 399 ms, respectively), and for long words, $F_1(2, 80) = 13.81$, $MSE = 3,927$, $p < .0001$; $F_2(2, 140) = 6.15$, $MSE = 3,062$, $p < .01$ (the means were 280, 302, and 351 ms, respectively). The interaction reflects the fact that medium-length, low-frequency words resulted in shorter first fixations than did other low-frequency words, $F_1(2, 80) = 9.38$, $MSE = 7,555$, $p < .001$; $F_2(2, 140) = 8.62$, $MSE = 3,062$, $p < .001$, and medium-length, high-frequency words resulted in longer first fixations than did other high-frequency words, $F_1(2, 80) = 3.86$, $MSE = 3,867$, $p < .05$; $F_2(2, 140) = 2.18$, $MSE = 3,062$, $p = .12$.

The average first-fixation duration did not differ between dyslexic and nondyslexic participants ($F < 1$), nor was the grouping factor involved in any significant interaction.

First-Pass Reading

In this section, we report the gaze duration (i.e., the summed fixation time) and the number of fixations associated with the first-pass reading (see Table 3). All fixations that fell on a word before fixating away from it were included in the two measures. The main effect of word length was highly significant both for the gaze duration, $F_1(2, 80) = 94.37$, $MSE = 37,451$, $p < .0001$; $F_2(2, 140) = 10.07$, $MSE = 120,846$, $p = .0001$ (the means were 489, 530, and 798 ms, for the short, medium-length, and long words, respectively), as well as for the fixation frequency, $F_1(2, 80) = 84.07$, $MSE = 0.422$, $p < .0001$; $F_2(2, 140) = 15.80$, $MSE = 0.782$, $p < .0001$ (the means were 1.5, 1.8, and 2.5 for the short, medium-length, and long words, respectively). All pairwise contrasts were significant by subjects (all $ps < .001$), whereas in the item analyses long words differed from medium-length and short words ($p < .01$). The word-length effect seemed to be due primarily to longer words attracting more fixations, thus increasing the gaze duration. As we showed above, in the separate analysis of the duration of only the initial fixation, the main effect of word length was far from significant (see Kliegl et al., 1983, for a similar result).

There was a highly significant main effect of word frequency, again both for the gaze duration, $F_1(2, 80) = 254.26$, $MSE = 23,772$, $p < .0001$; $F_2(2, 140) = 30.00$, $MSE = 120,846$, $p < .0001$ (the means were 401, 480, and 813 ms, for the high-, medium-, and low-frequency words, respectively), and for the fixation frequency, $F_1(2, 80) = 101.38$, $MSE = 0.469$, $p < .0001$; $F_2(2, 140) = 23.47$, $MSE = 0.782$, $p < .0001$ (the means were 1.5, 1.7, and 2.7 for the short, medium-length, and long words, respectively). All pairwise contrasts were highly significant by subjects (all $ps < .0001$), whereas in the item analyses low-frequency words differed from medium- and high-frequency words ($p < .01$). The word-frequency effect was not entirely a result of more fixations being made on the relatively more infrequent words. This became apparent in the separate analysis of the first-fixation duration (see above), which showed a highly significant main effect of word frequency.

Table 3
Gaze Duration (in Milliseconds) and Number of First-Pass Fixations (in Parentheses) as a Function of Word Frequency and Word Length in Dyslexia and Control Groups

Word length	High	Medium	Low	*M*
	Dyslexia group			
Short	341 (1.3)	412 (1.4)	731 (1.8)	495 (1.5)
Medium	417 (1.5)	572 (2.0)	677 (2.1)	555 (1.9)
Long	485 (1.8)	447 (1.7)	1,355 (3.9)	762 (2.5)
M	414 (1.5)	477 (1.7)	921 (2.6)	604 (2.0)
	Control group			
Short	339 (1.2)	435 (1.5)	678 (1.8)	484 (1.5)
Medium	421 (1.5)	495 (1.8)	597 (2.0)	504 (1.8)
Long	505 (1.8)	519 (1.8)	1,474 (4.3)	833 (2.6)
M	422 (1.5)	483 (1.7)	916 (2.7)	607 (2.0)

(Columns High, Medium, Low under the spanning header "Word frequency".)

The Frequency × Length interaction proved significant for gaze duration, $F_1(4, 160) = 52.32$, $MSE = 44,345$, $p < .0001$; $F_2(2, 140) = 8.02$, $MSE = 120,846$, $p < .0001$, as well as for fixation frequency, $F_1(4, 160) = 44.30$, $MSE = 0.411$, $p < .0001$; $F_2(2, 140) = 9.91$, $MSE = 0.782$, $p < .0001$. The interaction reflects the fact that long, low-frequency words attracted considerably more fixations and longer gaze durations than did other low-frequency words. An analysis of simple effects indicated that for both dependent measures the word-length effect was separately significant for all word frequencies (all $ps < .0001$) and the word-frequency effect was separately significant for all word lengths (all $ps < .0001$).

Dyslexics did not differ from nondyslexics in the gaze duration (both $Fs < 1$), nor in the number of fixations (both $Fs < 1$; see Table 3). In the subject analysis, the grouping variable interacted with word length for gaze duration, $F_1(2, 80) = 3.24$, $MSE = 37,451$, $p < .05$, but the interaction was far from significant in the item analysis ($F_2 < 1$), suggesting that the effect was not consistent across target words.

The final analysis of the first-pass data concerned the frequency of dyslexic and nondyslexic participants making a forward (i.e., from left to right) versus regressive (i.e., from right to left) initial saccade immediately after the first fixation on the target word. The oculomotor dysfunction hypothesis would predict more regressive saccades for dyslexics. Only those target items that were read correctly (see below for the analysis of reading errors) were included in the analysis. Saccades landing subsequently on the target word itself or outside the target word were both considered. The two groups did not differ in the amount of regressive fixations, $\chi^2(1) = 1.55$, $p > .1$; the probability of making a regression was .34 for nondyslexics and .36 for dyslexics.

Second-Pass Reading

Second-pass reading (also called reinspections) includes all the fixations that landed on the word after the reader had fixated at least once away from it. Both the summed fixation time and the number of fixations associated with the second-pass reading are reported below. The main effect of word length was significant for fixation duration, $F_1(2, 80) = 5.51$, $MSE = 207,811$, $p < .01$; $F_2(2, 140) = 4.31$, $MSE = 142,324$, $p < .025$, and for fixation frequency, $F_1(2, 80) = 21.96$, $MSE = 0.232$, $p < .0001$; $F_2(2, 140) = 6.33$, $MSE = 0.285$, $p < .01$. Analyses of contrasts showed that long words differed reliably from short ($p < .1$ by subjects; $p < .01$ by items) and medium-length words (both ps $< .01$), but short words did not differ from medium-length words (see Table 4).

The main effect of word frequency reached significance both for fixation duration, $F_1(2, 80) = 64.35$, $MSE = 219{,}150$, $p < .0001$; $F_2(2, 140) = 24.52$, $MSE = 142{,}324$, $p < .0001$, and for fixation frequency, $F_1(2, 80) = 65.89$, $MSE = 0.314$, $p < .0001$; $F_2(2, 140) = 27.88$, $MSE = 0.285$, $p < .0001$. All pairwise contrasts were significant by subjects (all ps $< .001$); in the item analyses, low-frequency words differed from other words ($p < .01$).

In addition, there was a significant Frequency × Length interaction for the fixation duration, $F_1(4, 160) = 13.01$, $MSE = 183{,}617$, $p < .0001$; $F_2(4, 140) = 3.76$, $MSE = 142{,}324$, $p < .01$, and for the fixation frequency, $F_1(4, 160) = 10.71$, $MSE = 0.253$, $p < .0001$; $F_2(4, 140) = 3.80$, $MSE = 0.285$, $p < .01$. An analysis of simple effects revealed that for high- and medium-frequency words the word-length effect was not significant, whereas for low-frequency words the effect reached significance ($p < .001$). As is evident from Table 4, long, low-frequency words attracted by far the longest reinspection times.

Dyslexics had longer reinspection times in the subject analysis, $F_1(1, 40) = 9.26$, $MSE = 316{,}050$, $p < .01$; $F_2(1, 140) = 1.65$, $MSE = 142{,}324$, $p > .1$, the overall means being 696 ms for dyslexic participants and 520 ms for nondyslexic participants. The nonsignificant item analysis suggests that the group difference was restricted to a few target words only. An analogous, although statistically marginal, tendency was observed in the item analysis for the average number of reinspections, which could not be confirmed by the subject analysis, $F_1(1, 40) = 2.46$, $MSE = .967$, $p > .1$; $F_2(1, 140) = 3.46$, $MSE = .285$, $p = .065$.[3]

Reading Errors

Because the participants read the texts aloud, we were able to relate oral reading to eye behavior. Specifically, we examined whether a correlation could be found between different types of reading errors and the corresponding eye fixation patterns. The error frequencies are reported in Table 5 for different types of reading errors separately for nondyslexic and dyslexic participants. We distinguished four types of reading errors: (a) The target word was substituted by a nonword response (e.g., *competent* was read as *compendent*), (b) the target word was replaced by another word (e.g., *traversed* was read as *traveled*), (c) a morphological reading error (e.g., *headed* was read as *head*), and (d) an omission (i.e., no response). Moreover, correct responses were categorized in four response types: responses that were initially incorrect but were subsequently corrected, repeated responses, nonfluent responses (the participant had to struggle to get the correct pronunciation), and responses that were immediately correct.

Table 4
Summed Duration (in Milliseconds) and Number of Second-Pass Fixations (in Parentheses) as a Function of Word Frequency and Word Length in Dyslexia and Control Groups

Word length	Word frequency			
	High	Medium	Low	*M*
	Dyslexia group			
Short	330 (0.4)	553 (0.4)	1,249 (1.4)	711 (0.7)
Medium	454 (0.5)	632 (0.7)	641 (0.8)	576 (0.7)
Long	325 (0.5)	618 (0.8)	1,460 (1.9)	801 (1.1)
M	370 (0.5)	601 (0.6)	1,117 (1.4)	696 (0.8)
	Control group			
Short	299 (0.3)	329 (0.4)	932 (1.1)	520 (0.6)
Medium	278 (0.4)	556 (0.5)	493 (0.7)	442 (0.5)
Long	246 (0.5)	466 (0.7)	1,080 (1.4)	598 (0.9)
M	274 (0.4)	450 (0.5)	835 (1.1)	520 (0.7)

As is evident from Table 5, somewhat more errors were made by dyslexic than by nondyslexic participants, which was confirmed by a Pearson's chi-square test, $\chi^2(1, N = 42) = 22.91$, $p < .0001$. Dyslexic participants made twice as many word substitution and morphological errors and about 50% more nonword substitution errors than did nondyslexic participants. Of all the nonword substitution errors, 95% occurred on low-frequency words; this was true for 76% of all the word substitution errors. Morphological errors were distributed more widely over different word types, although 54% of them were made on long words.

In a subsequent analysis, we compared eye fixation patterns on those target words that resulted in an incorrect reading (for a similar kind of analysis of an aphasic patient, see Laine, Niemi, Koivuselkä-Sallinen, & Hyönä, 1995). The analysis was computed using target items as the random factor. Because the vast majority of reading errors were made on low-frequency words, we included as a control condition all the low-frequency target words that resulted in an immediately correct reading. We report data for the number of fixations in the first-pass and second-pass reading; the fixation time data resemble closely the fixation frequency data. For this analysis, second-pass fixations were clustered into two categories: those fixations that were launched back to the target word from a previous word and those fixations that came from a subsequent word. The relevant difference is that fixations of the former type were preceded by a regression away from the target word, whereas for the latter type of fixations the target word was initially left with a progressive saccade. We hoped that such a more detailed analysis would capture possible qualitative differences in the eye fixation patterns with respect to the type of reading error.

In Table 6, the number of first-pass fixations and the two types of second-pass fixations are presented for different types of oral reading errors. For each dependent measure, a set of t tests was performed to compare fixation frequencies associated with different error categories. In the following, differences are reported for which the p value was less than .01 using pooled-variance t tests.

---

[3] All the analyses reported above were repeated by excluding words that resulted in an incorrect reading. The new analyses yielded the exactly same effects as the original analyses. The only noticeable difference was in the means for the summed fixation time in second-pass reading, which were generally shorter when incorrectly read words were excluded.

Table 5
Frequency of Reading Errors (in %) in Dyslexia and Control Groups

Response time	Group	
	Dyslexia	Control
Correct responses	88.3	93.1
Immediately correct	82.3	87.9
Correct after self-correction	1.7	1.2
Repetition of correct reading	1.4	1.1
Struggle in pronunciation	2.9	2.9
Incorrect responses	11.7	6.9
Omission	0.1	0.1
Nonword substitution error	6.6	4.5
Word substitution error	3.1	1.4
Morphological error	1.9	0.9

Participants with dyslexia made significantly more first-pass fixations on words that resulted in a nonword response than on words that resulted in any other response (all $ps < .001$). However, word substitution errors and morphological errors did not differ from the correctly read items. Among controls, both nonword errors and word substitution errors were associated with more first-pass fixations than correctly read words ($p < .001$). Nonword responses also differed from morphological errors ($p < .01$), whereas morphological errors did not differ from correct responses. The major difference between dyslexic and nondyslexic participants was that the number of fixations made by dyslexic participants on a word that resulted in a word substitution error was significantly less than among nondyslexic participants ($p < .01$).

There were no significant effects for those second-pass fixations that were launched from a previous word, except that dyslexic participants' nonword responses were associated with more fixations than were nondyslexic participants' correct responses ($p < .001$). However, second-pass fixations returning back to the target word from a subsequent word were more affected by oral reading. First, nondyslexic participants made more second-pass fixations back to target words that resulted in a nonword response rather than a correct response ($p < .001$) or a word substitution error ($p < .01$). Similarly, dyslexic participants' nonword responses were associated with more second-pass fixations than were other responses (all $ps < .001$).

Table 6
Number of First-Pass and Second-Pass Fixations for Different Types of Oral Reading Errors in the Dyslexia and Control Groups

Fixation	Group	
	Dyslexia	Control
First pass		
Correct reading	2.1	2.2
Nonword substitution	4.3	4.9
Word substitution	2.5	4.5
Morphological error	1.7	2.7
Second pass		
From a previous word	0.6	0.5
Nonword substitution	1.0	0.7
Word substitution	0.5	1.2
Morphological error	0.2	0.0
From a subsequent word		
Correct reading	0.3	0.3
Nonword substitution	1.8	1.3
Word substitution	0.6	0.3
Morphological error	0.3	0.3

A multivariate analysis of variance, using the two types of second-pass fixations as dependent variables, yielded a highly significant interaction with error type, $F(6, 2{,}064) = 21.48, p < .0001$. A subsequent analysis of simple effects showed that with nonword responses, participants made significantly more second-pass fixations from a subsequent word than from a previous word, $F(2, 1{,}032) = 142.54, p < .0001$, whereas with correct responses and word substitution errors, there were more second-pass fixations from a previous word, $F(2, 1{,}032) = 66.95, p < .0001$.

Discussion

The results were very straightforward: For both reading groups, we were able to establish highly reliable word-frequency and word-length effects. Words that were more difficult to recognize (i.e., long words as well as low-frequency words) received more fixations than words that were relatively easier to process (i.e., short and high-frequency words). The length and frequency effects were observed both for the initial encounter on a word as well as for the frequency of making a regression back to the target word. The effects were largely due to more difficult words attracting multiple fixations on them. This was particularly the case with the word-length effect. In addition, word frequency also influenced the duration of initial fixation on the target word. It was longest for low-frequency words and shortest for high-frequency words.

The pattern of results was very similar between dyslexic and nondyslexic participants. Thus, we conclude that both dyslexic and nondyslexic children's fixation patterns in reading reflect momentary variations in the relative ease of processing in a similar manner that has previously been observed for skilled adult readers. However, we were not able to find any evidence supporting the oculomotor dysfunction hypothesis (Pavlidis, 1981), which would have predicted that dyslexic children make more fixations generally and more regressions in particular, coupled with shorter fixation durations. None of these claims appeared to be supported in our data. It should be noted, however, that the oculomotor dysfunction hypothesis may still be maintained by restricting it to other types of oculomotor behavior, such as vergence movements, smooth pursuits, or express saccades.

The lack of differences between our dyslexic participants and younger controls is consistent with the developmental lag hypothesis. In other words, the eye movement patterns of people with dyslexia look comparable to what would be expected on the basis of their word recognition ability (see also Pirozzolo & Rayner, 1979). However, Olson, Wise, Conners, Rack, and Fulker (1989) have shown that this does not hold for some other types of reading and related language processes. They demonstrated that the ability of people with dyslexia to read pseudowords and to play language games requiring the manipulation of phonemes in words was substantially below what would be predicted on the basis of their reading level.

There are two decisions that have to be made during reading with respect to readers' eye movements: how long to stay fixating in the current location and where to go next. There is reason to believe that these decisions are governed by independent mechanisms (Rayner & McConkie, 1976). Consequently, one may argue that only one of the mechanisms operates dysfunctionally among people with dyslexia. If the "how long" part works inadequately, it will mean that the first-fixation duration or the gaze duration (i.e., the initial encounter with the word) would not reflect difficulties in word recognition. However, there is no evidence in our data supporting this notion. Alternatively, one may argue that the "where" mechanism is not functioning adequately. This is implied in Lovegrove's (1992) visual deficit hypothesis, which postulates a deficit in the transient system of vision that is sensitive to stimuli presented outside the foveal region. It is known from previous research that extrafoveal information is utilized in determining where to look next in a text (Rayner & Pollatsek, 1981). This kind of deficit would be implied in a greater number of regressive fixations and rereadings in the absence of any processing difficulties. Our data on second-pass fixations did not support this argument, as the number of second-pass fixations for correctly read items was highly similar between dyslexic and nondyslexic participants. Similarly, the frequency of making a regression immediately after the initial fixation on the target word was not greater for dyslexics.

In addition to differences resulting from word frequency on first pass reading, effects of word frequency were apparent on reinspections. In previous studies of adult readers, the effect has consistently shown up in gaze duration for the first inspection of the target word (Henderson & Ferreira, 1990, 1993; Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986) and often also in first-fixation duration (Inhoff & Rayner, 1986; Raney & Rayner, 1995; Rayner & Duffy, 1986; Rayner et al., 1989; Underwood et al., 1990). The finding that word frequency affects the first-fixation duration is compatible with the view that word frequency influences a relatively early stage of word processing. It is noteworthy, though, that this effect was observed particularly for low-frequency words. This is consistent with the idea that only robust effects are reflected in first-fixation duration (cf. Hyönä, 1993; Rayner & Pollatsek, 1987). In previous studies, reinspections have not usually been analyzed as a function of word frequency. Henderson and Ferreira (1993), the only study that did report reinspection data, observed significantly longer regressive fixation durations for low-frequency than for high-frequency words, not unlike in the present study. An analogous but nonsignificant trend was also found in the number of fixations.

The word-length effect primarily manifested itself in a greater number of fixations on longer words. The first-fixation duration was not influenced by word length, which was also shown to be the case in skilled reading (see Kliegl et al., 1983; Rayner & McConkie, 1976). The word-length effect was observed both in the first-pass and the second-pass reading. Long words attracted more fixations than did medium-length and short words. That reinspections of words are influenced by word length has not been previously observed among skilled readers. On the contrary, Carpenter and Daneman (1981) observed that word length did not correlate with the duration of regressive fixations. The obvious reason for this difference is the skilled readers' comparatively effortless processing of words, including long words.

In our study, word length was also found to interact with word frequency in all three of the eye movement measures we used. However, the interaction pattern was somewhat dissimilar in different parameters. In first-fixation duration, medium-length words did not produce a word-frequency effect, whereas for short and long words the effect was clearly significant. There is no obvious explanation for the absence of a word-frequency effect for medium-length words. The fact that the low-frequency words of medium-length tended to be slightly more frequent than other low-frequency words (there were no words with a frequency of zero) might have contributed to it. This does not explain, however, why first fixations for medium-length, high-frequency words tended to be longer than on other high-frequency words. In first-pass reading, however, the interaction was more readily interpretable. It reflected the fact that long, low-frequency words attracted by far the greatest number of fixations. In second-pass reading, the short and long, low-frequency words attracted considerably more reinspections than did other words. These words were the most infrequent words among the target words. Consequently, the first-pass fixations displayed the clearest and most general word-frequency and word-length effects, whereas for second-pass fixations the effects were restricted to a subset of words. The frequency of making a regression back to a word seemed to be more determined by word frequency than by word length. This argument was also supported by the absence of word-length effects for high- and medium-frequency words.

The analysis of reading errors demonstrated that participants with dyslexia made more oral reading errors than did their controls. This result is consistent with their lower scores on the PIAT word recognition test. The most typical error for both groups was a nonword substitution error, with dyslexic readers making them 50% more often than their nondyslexic peers. They appeared almost entirely on low-frequency words. This is not surprising as many of the low-frequency words were probably totally unfamiliar to our participants. The eye-movement analysis showed that for both groups nonword substitution errors were associated with additional first-pass fixations being devoted to words that resulted in such an error. A similar finding was observed for fixations that returned back from a subsequent word, but not for reinspections that were launched from a previous word. Thus, these results suggest that when encountering words that are particularly difficult to decode, young readers tend to continue reading beyond the cumbersome word, probably in the hope of finding additional cues for the word's identity from the subsequent context. Dyslexic participants were found to differ from nondyslexic participants in that they had no significant increase in the number of fixations on words where a real-word substitution error was made. Either the dyslexic readers were unaware of making an error or they were content to come up with a response that sounded reasonable. For both groups, words that produced morphological errors did not attract more fixations than did correctly read words. This is not surprising, as most of the morphological errors did not seriously modify the sentence meaning or introduce a syntactic error (e.g., *newspapers → newspaper; headed → head;* for grammatically incongruent morphological responses, however, see Hyönä & Lindeman, 1994).

It may be argued that our results obtained using a reading-aloud task would not necessarily generalize to silent reading. From the perspective of the oculomotor dysfunction hypothesis, one could perhaps claim that oral reading elicits a stronger link between reading eye movements and word recognition processes than does silent reading, whereby possible group differences in oculomotor functioning that would be observable in silent reading are masked in oral reading. On the basis of our study, we cannot rule out this possibility. However, we can safely argue that in oral reading, eye movements are closely linked with word recognition processes. From a different standpoint, one may also argue that word-frequency and word-length effects are strengthened by the task demands of oral reading. Assuming that readers stay fixating on a word until its pronunciation is completed, fixation times would also reflect pronunciation times. This assumption is not quite correct, however, as readers do not as a rule keep their eyes on the word that is being pronounced, but the voice lags behind the eyes usually by a couple of words (the so-called eye–voice span, see Levin, 1979). This applies to readers of different ability, except beginning readers with whom the word they are currently fixating and reading aloud usually coincides (see Rayner & Pollatsek, 1989, p. 364). It may be possible, nevertheless, that an oral reading task might bring about a more robust word-length and word-frequency effect than silent reading.

There are two eye movement studies where poorer readers' reading strategies were compared with those of better readers. Fletcher (1991) studied the error recovery strategies among normal and reading disabled adolescents (14–15 years of age) using semantically anomalous and syntactically ambiguous sentences. As in the present study, he did not find any major differences in the nature of reading strategies adopted by the two groups. The most commonly used strategy for both groups was to make longer first-pass fixations on the region that appeared inconsistent in the sentence, followed by an immediate rereading of that text segment. This is exactly the same pattern of eye movements that we observed for words that were difficult to decode. Murray and Kennedy (1988), however, did find differences in regressive fixation patterns among good- and poor-reading elementary school students in a task that primarily tapped comprehension processes. They found that good readers were able to "make efficient large regressive saccades to points in text containing relevant information" (p. 709), whereas poor readers performed less efficient "backtracking," that is, they exhibited a sequence of relatively short regressive saccades when resolving anaphoric references. It should be noted, however, that the total number of regressions per se did not differ between the two groups. The observed difference in the reading strategy was attributed to the difference in the ability to accurately code spatial information.

In conclusion, we wish to claim that children with dyslexia have eye movement patterns during reading that are not qualitatively different from those of normal children. This conclusion is based not only on the results of present study but also on previous analyses conducted by Olson's laboratory and by a number of other researchers. The previous studies have established marked within-group individual variation in eye movements both during reading and target search that were independent of reading ability and age (Olson, Conners, & Rack, 1991; Olson & Forsberg, 1993; Olson, Kliegl, Davidson, & Foltz, 1985; Olson, Rack, & Conners, 1991). These individual differences seemed to have some common origin, as eye movement parameters in reading and target search were found to correlate significantly. Part of this correlation may have been due to children transferring their reading style to target search, but there was also evidence suggesting an underlying genetic component. By making use of their monozygotic and dizygotic twin sample, Olson and colleagues observed a significant genetic influence for the proportion of progressive saccades both in reading and target search. The genetic influence on eye movements was independent from differences in reading ability. Because of the substantial individual variation in eye movement patterns, we feel that all claims for significant qualitative differences between dyslexic and nondyslexic children's eye movements during reading should be considered with great caution (see also McConkie et al., 1991).

References

Biscaldi, M., Fischer, B., & Aiple, F. (1994). Saccadic eye movements of dyslexic and normal reading children. *Perception, 23,* 45–64.

Black, J. L., Collins, D. W. K., DeRoach, J. N., & Zubrick, S. (1984). A detailed study of sequential saccadic eye movements for normal and poor reading children. *Perception & Motor Skills, 59,* 423–434.

Bogacz, J., Mendilaharsu, C., & Mendilaharsu, S. A. (1974). Electro-oculographic abnormalities during pursuit movements in developmental dyslexia. *Electroencephalography and Clinical Neuropsychology, 36,* 651–656.

Brown, B., Haegerstrom-Portnoy, G., Adams, A. J., Yingling, C. D., Galin, D., Herron, J., & Marcus, M. (1983). Predictive eye movements do not discriminate between dyslexic and control children. *Neuropsychologia, 21,* 121–128.

Carpenter, P. A., & Daneman, M. (1981). Lexical retrieval and error recovery in reading: A model based on eye fixations. *Journal of Verbal Learning and Verbal Behavior, 20,* 137–160.

Carroll, J. B., Davies, P., & Richman, B. (1971). *Word frequency book.* Boston: Houghton Mifflin.

Cohen, A. H. (1988). The efficacy of optometric vision therapy. *Journal of the American Optometric Association, 59,* 95–105.

Dixon, W. D. (Ed.). (1990). *BMDP Statistical Software.* Berkeley, CA: University of California Press.

Dunn, L. M., & Markwardt, F. C. (1970). *Examiner's manual: Peabody Individual Achievement Test.* Circle Pines, MN: American Guidance Service.

Eden, G. F., Stein, J. F., Wood, H. M., & Wood, F. B. (1994). Differences in eye movements and reading problems in dyslexic and normal children. *Vision Research, 34,* 1345–1358.

Fields, H., Wright, S., & Newman, S. (1993). Saccadic eye movements while reading and tracking, in dyslexics, reading-matched, and IQ-matched children. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 309–319). Amsterdam: North-Holland.

Fischer, B., Biscaldi, M., & Otto, P. (1993). Saccadic eye movements of dyslexic adult subjects. *Neuropsychologia, 31,* 887–906.

Fischer, B., & Weber, H. (1990). Saccadic reaction times of dyslexic and age-matched normal subjects. *Perception, 19,* 805–818.

Fletcher, J. (1991). Qualitative descriptions of error recovery patterns across reading level and sentence type: An eye movement analysis. *Journal of Learning Disabilities, 24,* 568–575.

Griffin, D. C., Walton, H. N., & Ives, V. (1974). Saccades as related to reading disorders. *Journal of Learning Disabilities, 7,* 310–316.

Heiman, J. R., & Ross, A. O. (1974). Saccadic eye movements and reading difficulties. *Journal of Abnormal Child Psychology, 2,* 53–61.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 417–429.

Henderson, J. M., & Ferreira, F. (1993). Eye movement control during reading: Fixation measures reflect foveal but not parafoveal processing difficulty. *Canadian Journal of Experimental Psychology, 47,* 201–221.

Hyönä, J. (1993). *Eye movements during reading and discourse processing.* Psychological Research Reports 65, Turku, Finland: University of Turku.

Hyönä, J., & Lindeman, J. (1994). Syntactic context effects on word recognition: A developmental study. *Scandinavian Journal of Psychology, 35,* 27–37.

Hyönä, J., Niemi, P., & Underwood, G. (1989). Reading long words embedded in sentences: Informativeness of word halves affects eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 142–152.

Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behavior, 23,* 612–624.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40,* 431–439.

Inhoff, A. W., Topolski, R., Vitu, F., & O'Regan, J. K. (1993). Attention demands during reading and the occurrence of brief (express) fixations. *Perception & Psychophysics, 54,* 814–823.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87,* 329–354.

Kavale, K., & Mattson, P. D. (1983). One jumped off the balance beam: Motor training. *Journal of Learning Disabilities, 16,* 165–173.

Kliegl, R., & Olson, R. K. (1981). Reduction and calibration of eye-monitor data. *Behavior Research Methods and Instrumentation, 13,* 115–120.

Kliegl, R., Olson, R. K., & Davidson, B. J. (1983). On problems of unconfounding perceptual and language processes. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 333–343). New York: Academic Press.

Laine, M., Niemi, J., Koivuselkä-Sallinen, P., & Hyönä, J. (1995). Morphological processing of polymorphemic nouns in a highly inflecting language. *Cognitive Neuropsychology, 12,* 457–502.

Levin, H. (1979). *The eye–voice span.* Cambridge, MA: MIT Press.

Lovegrove, W. (1992). The visual deficit hypothesis. In N. Singh & I. Beale (Eds.), *Learning disabilities: Nature, theory, and treatment* (pp. 246–269). New York: Springer-Verlag.

Martos, F. J., & Vila, J. (1990). Differences in eye movement control among dyslexic, retarded and normal readers in the Spanish population. *Reading and Writing: An Interdisciplinary Journal, 2,* 175–188.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics, 46,* 245–253.

McConkie, G. W., Zola, D., Grimes, J., Kerr, P. W., Bryant, N. R., & Wolff, P. M. (1991). Children's eye movements during reading. In J. F. Stein (Ed.), *Vision and visual dyslexia* (pp. 251–262). London: Macmillan.

Murray, W. S., & Kennedy, A. (1988). Spatial coding in the processing of anaphor by good and poor readers: Evidence from eye movement analyses. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 40(A),* 693–718.

Olson, R. K., Conners, F. A., & Rack, J. P. (1991). Eye movements in dyslexic and normal readers. In J. F. Stein (Ed.), *Vision and visual dyslexia* (pp. 243–250). London: Macmillan.

Olson, R. K., & Forsberg, H. (1993). Disabled and normal readers' eye movements in reading and non-reading tasks. In D. Willows, R. Kruk, & E. Corcos (Eds.), *Visual processes in reading and reading disabilities* (pp. 377–391). Hillsdale, NJ: Erlbaum.

Olson, R. K., Kliegl, R., & Davidson, B. J. (1983). Dyslexic and normal readers' eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 816–825.

Olson, R. K., Kliegl, R., Davidson, B. J., & Foltz, G. (1985). Individual and developmental differences in reading disability. In G. E. MacKinnon & T. G. Waller (Eds.), *Reading research: Advances in theory and practice.* (Vol. 4, pp. 1–64). New York: Academic Press.

Olson, R. K., Rack, J. P., & Conners, F. A. (1991). Eye movements and their heritability in dyslexic and normal readers. In R. Schmid & D. Zambarbieri (Eds.), *Oculomotor control and cognitive processes* (pp. 503–513). Amsterdam: North-Holland.

Olson, R. K., Wise, B., Conners, F., Rack, J., & Fulker, D. (1989). Specific deficits in component reading and language skills: Genetic and environmental influences. *Journal of Learning Disabilities, 22,* 339–348.

O'Regan, J. K. (1992). Optimal viewing position in words and the strategy–tactics theory of eye movements in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 334–354). New York: Springer-Verlag.

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

Pavlidis, G. Th. (1983). The "dyslexia syndrome" and its objective diagnosis by erratic eye movements. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 441–466). New York: Academic Press.

Pirozzolo, F. J., & Rayner, K. (1979). The neural control of eye movements in acquired and developmental reading disorders. In H. A. Whitaker & H. A. Whitaker (Eds.), *Studies in neurolinguistics* (Vol. 4, pp. 97–123). New York: Academic Press.

Raney, G. E., & Rayner, K. (1995). Word frequency effects and eye movements during two readings of a text. *Canadian Journal of Experimental Psychology, 49,* 151–172.

Raymond, J. E., Ogden, N. A., Fagan, J. E., & Kaplan, B. J. (1988). Fixational instability and saccadic eye movements of dyslexic children with subtle cerebellar dysfunction. *American Journal of Optometry and Physiological Optics, 65,* 174–181.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85,* 618–660.

Rayner, K. (1985). Do faulty eye movements cause dyslexia? *Developmental Neuropsychology, 1,* 3–15.

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 14,* 191–201.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16,* 829–837.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 33(A),* 351–373.

Rayner, K., & Pollatsek, A. (1987). Eye movements in reading: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 327–362). Hillsdale, NJ: Erlbaum.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading.* Englewood Cliffs, NJ: Prentice Hall.

Rayner, K., Sereno, S. C., Morris, R., Schmauder, A. R., & Clifton, C. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes, 4,* 21–49.

Rubino, C. A., & Minden, H. A. (1973). An analysis of eye-movements in children with a reading disability. *Cortex, 9,* 217–220.

Spache, G. D. (1963). *Diagnostic reading scales.* New York: McGraw Hill.

Stanley, G., Smith, G. A., & Howell, E. A. (1983). Eye movements and sequential tracking in dyslexic and control children. *British Journal of Psychology, 74,* 181–191.

Stein, J. F., & Fowler, M. S. (1985). Effect of monocular occlusion on visuomotor perception and reading in dyslexic children. *Lancet, 13,* 69–73.

Taylor, S. (1965). Eye movements while reading: Facts and fallacies. *American Educational Research Journal, 2,* 187–202.

Underwood, G., Hubbard, A., & Wilkinson, H. (1990). Eye fixations predict comprehension: The relationships between reading skill, reading speed, and visual inspection. *Language and Speech, 33,* 69–81.

Venezky, R. L. (1993). History of interest in the visual component of reading. In D. M. Willows, R. S. Kruk, & E. Corcos (Eds.), *Visual processes in reading and reading disabilities* (pp. 3–30). Hillsdale, NJ: Erlbaum.

Wechsler, D. I. (1974). *Examiner's manual: Wechsler Intelligence Scale for Children—Revised.* New York: Psychological Corporation.

Received May 31, 1994
Revision received November 21, 1994
Accepted December 6, 1994 ■