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first published in:
Eye movements in reading : perceptual and language processes / ed. by Keith Rayner. - New York [u.a.] : Acad. Press, 1983. - (Perspectives in neurolinguistics, neuropsychology, and psycholinguistics), S. 467-479

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Eye Movements in Reading Disability[1]

I. Introduction

The relation between eye movements and reading skill has intrigued psychologists and educators for nearly a century. The traditional experimental approach has been to compare group means for good and disabled readers on general eye movement parameters such as duration and number of fixations, frequency of regressions, and saccade length. The common result has been longer duration and higher fixation frequency, more regressions, and shorter saccades for average disabled readers when reading the same material as the average good reader (Tinker, 1965). Our research on these general parameters differs from the earlier studies in two important aspects. The reading materials are adjusted for each reader's word recognition skill, and our major focus is on individual differences in eye movements in relation to other reading and cognitive processes within the reading disabled group.

Recent neurologically oriented case studies of disabled readers have shown that acquired and congenital brain defects result in distinct subtypes of eye movement abnormalities (see Pirozzolo & Rayner, 1978a, for a review). A case reported by Pirozzolo and Rayner (1978b) showed an abnormal tendency to fixate from right to left along a line of text. They speculated that this was probably associated with a

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[1] This research was supported by USPHS program project grant HDMH 11681-01A1. In the program project, subjects were first tested with several psychometric measures in Dr. DeFries's laboratory at the Institute for Behavior Genetics. The present report uses the WISC-R I.Q. and PIAT reading tests from this session.

congenital parietal lobe dysfunction. In contrast, a second case reported by Pirozzolo and Rayner displayed normal eye movements when reading very easy text, but showed the frequently reported increase in fixations and regressions of disabled readers when he read text above his level of skill.

Other neurological case studies also indicate substantial individual differences in word coding processes, with brain injury giving rise to distinct patterns of reading disorders (e.g., Coltheart, 1981; Marshall & Newcombe, 1973). Several investigators have suggested that these reading disorder subtypes can be related to the selective impairment of visual and phonological word coding systems (Saffran & Marin, 1977; Shallice & Warrington, 1980). Coltheart (1981) has argued that similar differences in coding skills may exist within the general reading disabled population. In fact, these individual differences have been observed by several investigators (see Satz & Morris, 1981, for a review).

This chapter specifically addresses the relationship between individual differences in word coding processes and eye movements in reading disability. Our broader goal is to understand the nature of individual differences in reading disability through a convergent perspective on several different reading process parameters.

Our reading disabled subjects participated in a project dealing with differential diagnosis in reading disability through the University of Colorado Institute for Behavior Genetics. They were first tested with several standard psychometric measures such as the WISC-R IQ test and the Peabody Individual Achievement Test (PIAT). Subjects who met the selection criteria, to be described, were tested in our laboratory for word coding processes and eye movements.

The definition of specific reading disability in the project includes a WISC verbal or performance IQ of at least 90, no obvious neurological or emotional problems, normal socioeconomic and educational background, and reading skill at approximately half of expected grade level. Forty-four reading disabled subjects (34 males and 10 females) and 42 normal subjects (35 males and 7 females) were included in the present analyses. Age in both groups ranged from 13–17 years. Mean age, WISC full-scale IQ, and PIAT grade-equivalent subscores for word recognition, spelling, and comprehension are presented in Table 26.1. The subjects were drawn from the Boulder, Colorado, area where socioeconomic levels and quality of schools are above average for the country. The normal group is also above the national norms in reading skill. However, the reading disabled group is substantially below average despite their normal intelligence and their above average socioeconomic level and educational background. Thus, their reading failure cannot be attributed to general intelligence or environmental deficits.

II. Word Coding Processes

A. Word Recognition

Three tasks considered in this chapter were part of a series designed to assess various word coding processes. The first tested word recognition skill by presenting lists of 20 words across several grade levels from the Camp and McCabe (1977) reading and spelling test. The words were presented singly, in lowercase, three characters per degree of visual angle, on a television monitor placed 36 in. from the subject. Vocalization latency was monitored by a voice key. The first list presented was at least two grade levels below the subject's PIAT reading recognition score. Successively higher grade level lists were presented until the subject failed to recognize at least 50% of the words within the 2-sec time limit. The grade level list that was closest to 50% errors determined the subject's word recognition grade level.

B. Orthographic Coding

Orthographic and phonological coding tasks were adapted from a study of normal adult individual differences by Baron and Strawson (1976), (see Davidson, Kliegl, & Olson, 1981, for further details). In the orthographic coding task, subjects were presented 8 practice and 40 test trials containing two letter strings displayed side by side. One letter string was a word (e.g., *rain*), whereas the other was a phonologically identical nonword (e.g., *rane*). The subject's task was to press one of two buttons indicating whether the string to the left or to the right was a word. They were told to respond as quickly as possible but to try to avoid errors. Error and latency feedback were presented on the television monitor screen between trials.

C. Phonological Coding

Phonological coding skill has been identified by many researchers as the most substantial and fundamental difference between groups of good and disabled readers (see Rozin & Gleitman, 1977, for a review). Our test of individual differences in this skill was identical in structure to the orthographic task, except that neither of the letter strings was a word (e.g., *kake* and *dake*). However, one of these nonwords sounded like a word (e.g., *kake*). The target and distractor items were orthographically similar to each other and to the real word (e.g., *cake*) from which they were derived. As in the orthographic task, subjects pushed a button on the side of the perceived correct response and then received error and latency feedback. Again, the total stimulus series consisted of 8 practice and 40 test trials.

Recall that orthographic-task pairs were similar in phonology and, therefore, had to be discriminated primarily on the basis of orthographic differences. Phonology-task pairs presented no orthographic basis for lexical access but could be discriminated on the basis of phonology.

III. Eye Monitor and Reading Task

Following the word coding tasks, stories were presented for oral and silent reading while the subject's eye movements were recorded. Eye fixations were monitored with a Gulf & Western Applied Sciences Model 1996. This system uses infrared light to monitor pupil and corneal-reflection positions related to eye fixations. Fixation location was sampled at the rate of 60 Hz and the data were transfered to a PDP 11/03 computer for later analyses (Davidson, 1981).

During calibration and reading, subjects leaned forward into a goggles frame to stabilize head position. Calibration consisted of fixating each of nine points in a rectangular grid. Calibrated output of the eye monitor was later mapped to text locations with programs described in Kliegl and Olson (1981) and Kliegl (1981). Accuracy of the system was within one character position on 90% of the fixations. These programs also reduced the 60 Hz eye position data to fixations and moves yielding the fixation duration, regression, and saccade length measures used in the following analyses.

The stories were adapted from the Spache (1963) Diagnostic Reading Scales and were selected for grade level difficulty based on the subject's score in the earlier word recognition test. The stories ranged from one to two screens of text, 11 lines per screen, and about 60 character spaces wide (20° of visual angle). Following the eye movement calibration the subject was told to read the first story aloud and to remember it for a test of eight questions at the end of the story. After the first test, eye position was recalibrated and the second story was presented for silent reading, followed by an eight question test. We will begin the presentation and discussion of results with the group data and then proceed to our main concern: individual differences within the disabled reader group.

IV. Group Differences

Group data for word recognition grade level, orthographic reaction time, orthographic errors, phonological reaction time, and phonological errors are presented in Table 26.1. The results confirm that there are substantial group differences in word recognition and related coding skills.

Eye fixation measures presented in Table 26.2 include fixation duration, saccade length, Regressive Fixation Index (RFI), percentage of regressions, and reading rate in words per minute (wpm). Sample sizes are given in parentheses. The *N*'s were different for reading aloud and silent because adequate data were not available for all subjects in both conditions.

The percentage of regression was computed by dividing the number of regressive fixations by the total number of fixations. These values are comparable to other studies (Tinker, 1965). For the individual difference analyses, a RFI was calculated by dividing the number of regressive fixations by the number of fixations that were preceded and succeeded by a right going saccade. Thus, fixations at the beginning and end of a line and fixations preceding a regressive fixation were not included. The RFI measure was thought to be a purer measure of regression tendencies than percentage of regressions, but in fact the correlation between the two measures was .97. Saccade length was computed by including only those forward saccades that were preceded and succeeded by a right going saccade. Saccades following a regression were excluded because subjects tend to

TABLE 26.1
Standardized Test and Word Coding Scores

			PIAT			Orthographic		Phonological		Word recognition
	Age	WISC	Recognition	Spelling	Comprehension	Latency	Errors	Latency	Errors	
Normal (n=42)										
x[a]	15.9	112	10.7	9.3	10.6	801	8.4	1318	17.4	11.9
(s)[b]	(1.5)	(8)	(2.1)	(2.4)	(2.0)	(129)	(5.9)	(354)	(12.4)	(1.2)
Disabled (n=44)										
x	15.7	104	6.2	5.2	7.0	1054	13.3	2058	30.7	6.4
(s)	(1.4)	(10)	(2.1)	(1.6)	(2.4)	(311)	(6.0)	(909)	(13.8)	(2.5)

[a] x is the mean group score.

[b] (s) is the standard deviation.

TABLE 26.2
Group and Condition Means (Standard Deviations) for Eye Movement Parameters

		Regression index	Regressions %	Fixation duration	Saccade length	Words per minute
Normal						
Aloud	*x*[a]	40.4	18.0	300	6.0	148
(*n*=30)	(s)[b]	(17.9)	(5.1)	(30)	(.8)	(23)
Silent	*x*	44.0	19.2	283	7.1	158
(*n*=32)	(s)	(18.8)	(6.8)	(33)	(1.0)	(45)
Disabled						
Aloud	*x*	52.7	22.8	355	5.4	98
(*n*=33)	(s)	(18.2)	(4.4)	(57)	(.7)	(26)
Silent	*x*	53.8	25.5	333	5.9	111
(*n*=26)	(s)	(19.6)	(6.0)	(58)	(.8)	(32)

[a] *x* is the mean group score.
[b] (s) is the standard deviation.

skip over fixation locations that precede the regression, and this would artificially inflate the relation between RFI and saccade length.

All of the eye fixation group differences were significant, except for saccade length in the aloud condition. Although the differences were not as large as in previous studies because text difficulty was adjusted for word recognition skill, they follow the typical pattern of longer fixation duration, shorter saccades, and a higher percentage of regressive movements in disabled readers. The absence of a significant difference for saccade length in the aloud condition suggests that the good readers were restricted in their eye movements by the vocalization task. Saccade length increased significantly for good readers in the silent condition but not for the disabled readers.

V. Dimensions of Individual Differences

In this section we will discuss the separate relationships of word recognition, IQ, saccade length, and relative phonological skill to the RFI for disabled readers in the aloud condition. The subsequent section will combine these variables in multiple regression analyses for reader groups and conditions.

The standard deviations in Tables 26.1 and 26.2 indicate that there are substantial individual differences in IQ, word coding skills, and eye movement variables within the reading disabled group. The first question we asked was how these variables correlated with each other. The second step was to analyze selected variables in a series of theoretically motivated multiple-regression models.

Table 26.3 shows that RFI was significantly correlated with IQ, saccade length, and phonological latency. RFI was chosen as the criterion variable in the following models based on previous research and our initial hypotheses about how

TABLE 26.3
Correlations for Disabled Readers Reading Aloud

	Regressive fixation index	Word recognition	WISC	Saccade length	Phonological latency	Orthographic latency	Fixation duration
Word recognition	−.18						
WISC	.32	.38					
Saccade length	.56	.44	.48				
Phonological latency	.36	−.51	.07	.10			
Orthographic latency	−.14	−.38	.02	.03	.61		
Fixation duration	.05	−.44	−.30	−.22	.11	.03	
Words per minute	−.22	.74	.42	.42	−.41	−.13	−.63

the distribution of visual attention would relate to the other parameters. These hypotheses are described with the presentation of each of the following analyses.

A. Regressive Fixation Index and Word Recognition

The usual interpretation of a proportional increase in regressions with poor word recognition skill is that unknown words in the text elicit regressive saccades within words and to previous words for contextual support. We would expect this to be the case in the present study, if the adjustment of text difficulty for word recognition skill was not completely successful. Analyses of the oral reading errors showed that slightly more word recognition errors were made by subjects reading the lower-grade-level material. However, word recognition skill was not significantly related to RFI. Since RFI is a proportional score, its independence from word recognition does not imply that the low-grade-level material would be read with the same number of regressions; only the proportional increase is *independent.*

Although not significantly correlated with RFI, word recognition was correlated with the other variables that we use to predict RFI in the following three models. Since our main interest is in the influence of these variables, we use word recognition as a suppressor variable which removes variance in the predictors which is not related to RFI.

B. Regressive Fixation Index and IQ

IQ predicted 21% of RFI variance; the higher the IQ the higher the RFI. The predicted variance was 31% with one additional subject included in the initial analysis. This subject was not included in the final analysis because she was two standard deviations from the regression line. However, further consideration of her performance suggested a possible explanation for the relationship between IQ and RFI. Her word recognition, orthographic, and phonological skills were relatively good, but she had the lowest IQ (91) and the lowest RFI in the disabled reader group. She also had the lowest comprehension score. This general description fits the "word caller" syndrome (Goodman, 1968; Huttenlocher & Huttenlocher, 1973).

It may be characteristic of low IQ disabled readers that they do not monitor their understanding of the text and do not regress when comprehension breaks down. Disabled readers with high intelligence may more carefully monitor their understanding and would regress when necessary to integrate earlier with later text for comprehension. Although this seems to be a reasonable explanation of the IQ effect, other interpretations are possible. IQ is also correlated with saccade length ($r = .48$), and the following analysis will show that saccade length is the most powerful single predictor for RFI. When the complete regression model with all variables is evaluated, it will be shown that most of the variance shared between IQ and RFI is based on saccade length. This raises another possible explanation for the interrelation between IQ, RFI, and saccade length. Eyes of the more intelligent readers may take larger steps through the text. Sometimes this may result in overshooting the preferred center of a word, causing a short corrective regression within the word (O'Regan, 1980; Kliegl, Olson, & Davidson, Chapter 19 of this volume). This type of regression may combine with the comprehension and context related regressions described earlier to produce the effect of IQ on RFI. More research is needed to evaluate the various interpretations. This will involve the examination of the component scores in the WISC and the relation of eye fixations to specific text locations.

C. Regressive Fixation Index and Saccade Length

Saccade length predicted a substantial 53% of the variance in RFI. Subjects who made longer saccades also made relatively more regressions. There are several possible reasons for this result. At the perceptual level discussed earlier, long saccades could result in more frequent overshooting of the optimal position for fixating a word. At the cognitive level, long saccades could produce more frequent regressions if the subjects' gathering of visual information sometimes raced too far ahead of processes such as phonological coding, and syntactic and semantic analysis. A third hypothesis is that long saccades reflect a general processing strategy that depends on contextual support in the decoding of words. This strategy could be related to higher demands for comprehension among disabled readers with high IQ as well as the need to compensate for weak orthographic or phonological coding skills. The relationship of these skills to the RFI will be shown next.

D. Regressive Fixation Index and Relative Phonological Skill

Relative phonological skill is defined as the difference between the weighted logarithm of phonological latency and the weighted logarithm of orthographic latency. The weights were chosen to maximize the correlation of the difference with RFI. The model accounted for 34% of the variance in RFI. (Adding a similar calculation for the error rates resulted in a nonsignificant increase to 38%.)

Recall that these two tasks were considered to be tests of independent word coding skills (Baron & Strawson, 1976). However, orthographic latency was not significantly correlated with RFI. Because the two tasks are so similar in experimental procedure, subtracting orthographic latency reduces variance in phonological latency that is not associated with phonological skill. This extraneous variance could include subjects' general adaptation to the experimental situation and speed–accuracy criteria. In addition to the above view of the orthographic task as a control for extraneous variance, the adjusted phonological score is not independent of the orthographic score. In other words, what we call relative phonological skill is phonological skill relative to the subject's orthographic skill.

The finding that relatively poor phonological skill was associated with a relatively higher frequency of regressions was predicted. Our hypothesis was that stronger phonological codes would be associated with a more sequential left-to-right scanning strategy as graphemes were decoded to phonemes. Relatively weak phonological codes would be associated with less sequential processing within words and more frequent regressions to previous words to reinstate contextual support for decoding unfamiliar words. Weak phonological memory codes may also cause rapid forgetting of preceding text, resulting in a greater need for regressive fixations (Mark, Shankweiler, Liberman, & Fowler, 1977). Further discussion of the reasons for the relationship between RFI and relative phonological skill will be presented after the results from the silent reading condition.

VI. Multiple Regression Models of Individual Differences

A. Disabled Readers in the Aloud Condition

We have introduced three variables that alone or by interaction were significantly related to RFI during reading aloud. These variables were IQ, saccade length, and relative phonological latency. Word recognition skill served as a suppressor variable in all of the previous analyses. However, note that RFI variance related to word recognition (3%), IQ (21%), saccade length (53%), and phonological skill (34%) totals to 111%. Obviously there is some overlap in the variance these variables share with RFI. Composite Model 1 in Table 26.4 presents a hierarchical regression wherein the variables are entered in the order of word recognition, IQ, saccade length, and relative phonological latency. The *R*-squares show that for this sequence we always obtain significant increments. Relative phonological skill, entered on the final step, accounted for an additional 22% of the variance, compared with 31% when it was entered without IQ or saccade length. This regression model accounts for 78% of the RFI variance. To assess the

TABLE 26.4
Complete Models for Groups and Conditions

Disabled readers (aloud):						
RFI =	−4.41WR	+ 0.20IQ	+ 19.60SL	+ (32.55PL	− 101.26OL)	+ 129.69
SE:	.92	.10	3.08	13.45	19.25	52.74
R-square change:	.03	.21	.56		.78	
Disabled readers (silent):						
RFI =	−4.91WR	+ 0.36IQ	+ 13.53SL	+ (11.96PL	− 36.43OL)	+ 3.55
SE:	1.97	.19	4.18	27.63	43.32	115.09
R-square change:	.02	.22	.49		.51	
Normal readers (aloud):						
RFI =	−4.21WR	+ 0.06IQ	+ 14.09SL	− (18.21PL	− 55.08OL)	− 112.10
SE:	3.08	.20	4.37	38.66	64.22	193.34
R-square change:	.03	.08	.36		.38	
Normal readers (silent):						
RFI =	−4.75WR	− 0.14IQ	+ 7.29SL	+ (19.32PL	+ 4.82OL)	+ 7.89
SE:	3.93	.23	3.86	47.50	72.61	196.32
R-square change:	.06	.06	.16		.18	

RFI: Regressive fixation index
WR: Word recognition
IQ: WISC
SL: Saccade length
PL: Phonology latency
OL: Orthographic latency
SE: Standard errors of regression coefficients

independent contribution of the variables in the model they were excluded one at a time and the decrement of the *R*-square was tested for significance. It can be seen in Table 26.4 that excluding phonological skill caused a drop to 56% of the variance. Additional analyses showed that the exclusion of word recognition left 60%, dropping IQ left 75%, and dropping saccade length left 46%. IQ was the only variable that did not make a significant difference in the variance accounted for. Most of its variance is shared with the other variables, particularly saccade length.

B. Disabled Readers in the Silent Condition

The second model in Table 26.4 presents the results for the disabled readers in the silent condition. A significant difference between the aloud and silent models is the absence of an independent phonological skill effect in the silent condition. A possible reason for this difference is that the vocalization task presented an additional processing burden that may have been magnified for those who were weak in phonological skill, leading to greater word recognition, comprehension, and memory problems, and more associated regressions in the aloud condition. A related explanation would be that those who are slow in the generation of phonological codes would often find their eyes too far ahead of their voice in the aloud condition. In the silent condition, lexical access could be achieved visually and the slow generation of implicit phonological codes (postlexical access) would not require regressive fixations.

Our initial working hypothesis was that poor phonological skill would lead to more frequent regressions as the subject used contextual and visual information to aid in decoding unfamiliar words and focused less on the sequential phonemic decoding of letter patterns within words. We expected this hypothesized relation between eye movements and phonological skill to be valid for both aloud and silent reading conditions. Its absence in the silent condition suggests that the deployment of visual attention, indicated by RFI with these reading materials, is not systematically affected by phonological coding skill. Other eye movement parameters are being evaluated for their relation to relative phonological skill, and additional subjects are being tested with more difficult reading material. The materials in the present study were relatively easy, and the presence of more unfamiliar words may generate relationships between phonological skill and RFI in silent reading.

C. Normal Readers in Silent and Aloud Conditions

The only significant effect for normal readers was the *R*-square change of .08 to .36 when saccade length was entered in the aloud condition. A nonsignificant change of 10% was associated with saccade length in the silent condition. Thus, the only consistent effect across good and disabled readers was the relation between saccade length and the RFI. The absence of phonological effects for the good readers may be due to the fact that the good readers were generally high in phonological skill with much less variance. Also, the most difficult text, which all of the good readers read, was at the eighth-grade difficulty level. The relatively easy text and lack of word recognition problems may also have limited the effects of IQ.

VII. Conclusions

Our perspective on eye movements and reading disability is quite different from most previous research. The major focus is on individual differences *within* the reading disabled group, and several eye movement, reading process, and cognitive variables are explored simultaneously. What have we learned from this approach? First, it is clear that there were substantial individual differences between disabled readers that were independent of general reading skill. They varied widely in their relative frequency of regressive eye movements, length of saccades, IQ, and visual and phonological coding skills. Second, there was a strong relationship across individuals between different eye movement parameters. Those subjects who made longer saccades also tended to make relatively more regressive fixations. Third, there was a significant relationship between IQ, the RFI, and saccade length. Disabled readers with higher IQ tended to make longer saccades and have a higher RFI. Fourth, subjects who were weak in relative phonological skill tended to have a higher RFI, but only when reading aloud. Finally, all of the above relations were at least partially independent of word recognition skill. In establishing the existence of the above relations, we have raised new questions about their basis. Several hypotheses were offered to explain each of the relations. Additional analyses and research are needed to decide between them.

A general eye movement sequencing deficit in disabled readers has recently been proposed by Pavlidis (1981; Chapter 25 of this volume). He found that his reading disabled subjects had fixation problems in tracking a light that changed positions along a horizontal line. We have not observed this type of problem in our subjects while calibrating them, and the complex relations found between our variables do not seem explainable by a general eye movement deficit. Also, we did not confirm previous case study reports of some disabled readers' "irrepressible tendency" to scan text in a right to left direction (Ciuffreda, Bahill, Kenyon, & Stark, 1976; Gruber, 1962; Pirozzolo and Rayner, 1978b; Zangwill & Blakemore, 1972). These cases must be rare in our reading disabled population. Some disabled readers in our sample made more regressions than others, but these regressions were closely associated with word coding and higher cognitive processes.

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