Topical Review

The study of eye movements during reading has provided many important insights about the process of reading. Until recently, there has been a relatively broad consensus that the erratic eye movements of poor readers were a consequence of difficulties in learning the visual-verbal associations involved in reading, rather than being a primary cause of poor reading themselves. However, recent data has begun to question this assumption. In this month's Topical Review, the author reviews the research suggesting the erratic eye movements of dyslexics are not simply a consequence of poor reading skills. This research is important because, if it is substantiated in future work, examination of eye movement patterns may contribute significantly to the diagnosis of dyslexia. —J.K.T.

Eye Movements in Dyslexia: Their Diagnostic Significance

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Dyslexia affects the lives of millions of people worldwide and often has devastating psycho-socio-educational consequences. It is also one of the most controversial topics in the fields of developmental neurology, psychology, and education. The controversy arises from the incomplete definitions of the syndrome of dyslexia and from the contradictory theories that surround its etiology.

A major difference between dyslexia and other reading disabilities is that, unlike dyslexia, other categories of reading failure can be predicted on the basis of neurological, intelligence, socio-economic, educational, and psychological (motivational, emotional) factors known to adversely effect the reading process (Denckla, 1977; Dobbins, 1984; Downing & Thackray, 1975; Hollander, 1984; Symmes & Rapoport, 1972; Vernon, 1971). If, for instance, a child has problems in one or more of the above mentioned areas, he is expected to have reading problems. The extent of the reading disability is determined by the severity and number of factors that are involved.

In contrast, if a child has none of the above mentioned problems, he is expected to be a normal reader. Children can be classified as dyslexic when their failure to learn to read cannot be pedicted by deficiencies in any of the known causes of poor reading (Denckla, 1977; Rudel, 1980; Symmes & Rapoport, 1972). Psycho-socio-enviro-educational and intelligence factors do not cause dyslexia, although they can contribute to its severity or amelioration. The causes of dyslexia are constitutional (e. g. subtle brain malformation or malfunction) but they remain as yet undetermined. If dyslexia is due to neurological factors (Critchley, 1981; Masland, 1981), then there is no reason why dyslexia should not occur at all intelligence levels and in all psycho-socio-cultural backgrounds, as all other neurologically based conditions do.

CONCEPTUAL AND DEFINITIONAL PROBLEMS

Lack of knowledge of the causes of dyslexia has forced the adoption of definitions based on exclusionary criteria. This type of definition creates problems both to researchers and practitioners. These exclusionary criteria are often imprecise, unquantifiable and incomplete, a fact which often leads to the inclusion of an undetermined number of non-dyslexic retarded readers in samples of dyslexic children (Benton, 1975; Calfee, 1982; Denckla, 1977; Hughes, 1982; Pavlidis, 1983b). This, consequently, renders the results of such studies not specific to either reading retardation or dyslexia. One can not, therefore, reliably make inferences from these studies about dyslexia.

The diagnosis of dyslexia by the use of exclusionary criteria delays diagnosis (by at least 1.5 - 2 years after beginning school), which in turn can have the following negative effects: a) limited effectiveness of treatment following delayed diagnosis (Schiffman, 1968); and b) development of psychological problems secondary to reading failure. Furthermore, children cannot be unequivocally diagnosed as dyslexics if they are: a) psychologically maladjusted prior to beginning schooling; b) from a disadvantaged socio-cultural background; c) educationally deprived; and d) of low intelligence.

These problems stemming from a definition based on exclusionary criteria can be overcome only if a positive definition of dyslexia can be elaborated. Such a definition would identify dyslexics on the basis of positive behavioral, psychological and/or neurophysiological symptoms such as abnormal EEG or evoked potential and/or erratic eye movements (Duffy et al., 1980; Pavlidis, 1981a, b). A major advantage of a positive definition is that it would make possible an unequivocal diagnosis of dyslexia in children from disadvantaged socio-cultural and educational backgrounds, as well as in children who are psychologically disturbed or of low intelligence.

Unfortunately, our current knowledge does not lend itself to a positive definition of dyslexia. It is, therefore, imperative to utilize comprehensive exclusionary diagnostic criteria when studying dyslexia. In this way, all factors known to negatively influence the reading process can be taken into account (Downing & Thackray, 1975; Vernon, 1971; Rutter & Yule, 1975; Dobbins, 1984). Each of these factors has to be precisely defined and quantified in order to differentiate dyslexics from other disabled readers in a way that is replicable and meaningful (Pavlidis, 1981b). These general principles of subject selection have not usually been observed in studies of dyslexia/LD either for dyslexics or for the matched normal controls.

CONTROL GROUPS

Equally important to the subject selection criteria is the selection of appropriate control groups. It is customary to compare dyslexics with normal controls matched on I.Q., socioeconomic background, and chronological age. Such a comparison provides the degree of devia-

tion of the dyslexic's scores from the norm, but it does not frequently tell us much about the possible cause of those differences. This limitation can be overcome by the addition of a control group consisting of non-dyslexic retarded readers matched for both reading and chronological ages. Such a match can provide crucial information that could point to possible causal differences and even to a differential diagnosis between dyslexia and other forms of reading disability (Pavlidis, 1981b; 1983c). Such a differentiation could be achieved through behavioral, psychological, and/or psychophysiological tests such as EEG, evoked potentials, or eye movements.

THE SIGNIFICANCE OF EYE MOVEMENTS

Eye movement efficiency develops almost in parallel with the reading process. The importance of the use of eye movements as an objective tool for the study of the individual components of the reading process is further enhanced by the fact that the performance of our eye movements is beyond conscious control while performing a task and their analysis is automated, and hence, objective.

The functional significance of eye movements is far from being understood. Eye movements are the fastest and most frequent movements made by the human body. The eyes keep moving during sleep and even during coma (Coakley & Thomas, 1977). There are at least 4 different types of eye movements. Each type has its own neurological control system. The eye movement control system is one of the most complex, sophisticated and advanced biological control systems. The main type of eye movements used during visual scanning and reading are called saccadic eye movements or saccades. Saccades are preceeded and followed by pauses or fixations. The brain obtains its information through the eyes only during fixation. Furthermore, vision depends on the efficiency of eye movements. It is, however, *erroneous to equate eye movements with vision*, as the function of eye movement goes well beyond vision and reflects higher brain processes.

The significance of eye movements is such that a great part of the brain's potential is dedicated to their control. They serve not only vision but also a variety of high level cognitive functions. It is not, therefore, surprising that different types and characteristics of eye movements have been found to be among the first signs and most sensitive indices of many neurologically based conditions including schizophrenia, behavioral, and attentional disorders (Corvera et al., 1974; Holzman et al., 1976; Schwartz et al., 1984; Shagass et al., 1976; Von Noorden et al., 1964), and hyperactivity (Bala et al., 1981). They also are a good indicator of reading proficiency (Pavlidis, 1981b; Tinker, 1958).

Eye movements are a powerful method for uncovering and understanding the mechanisms involved in the reading process. Unlike other methods that provide only a global picture of the task under study, eye movements can be used to pinpoint the specific problems of the reader. By "mapping" the eye fixations on the text one can find which word or parts of the text attracted the reader's attention or were the most difficult. Such information is useful not only for uncovering problems in the different components of reading but also for the development of teaching strategies or methods appropriate for the child's personal strengths or weaknesses. A teacher can even monitor and further adjust his/her teaching strategy by following the child's progress through repeated eye movement measurements over time (Solan, in press). This objective procedure can be complementary to existing educational testing.

Up to now, the relatively high cost of eye movement devices, combined with the need for specialized technical skills for their operation, has restricted their use mainly to universities or other research-clinical institutions. When the above-mentioned problems are overcome, the benefits stemming from the application of eye movements technology to education will be appreciable.

EYE MOVEMENT AND READING DEVELOPMENT

Since its inception, research on eye movements has been intimately linked to the study of reading (Hue, 1908). This is a logical relationship, since eye movements constitute an integral part of the reading process. Interestingly, most of this research has concentrated on the study of normal readers (Tinker, 1958). Although little has been done to analyze the eye movements of learning disabled/dyslexic readers, the proven value of eye movements in uncovering the cognitive and perceptual skills of normal readers suggests that it will be useful to apply the ideas and technology of eye movement research to the study of LD/dyslexia.

Reading skills develop gradually, improving in precision and speed over the years. They develop in parallel with, and are clearly reflected in the patterns and characteristics of the readers' eye movements. Most of that development occurs

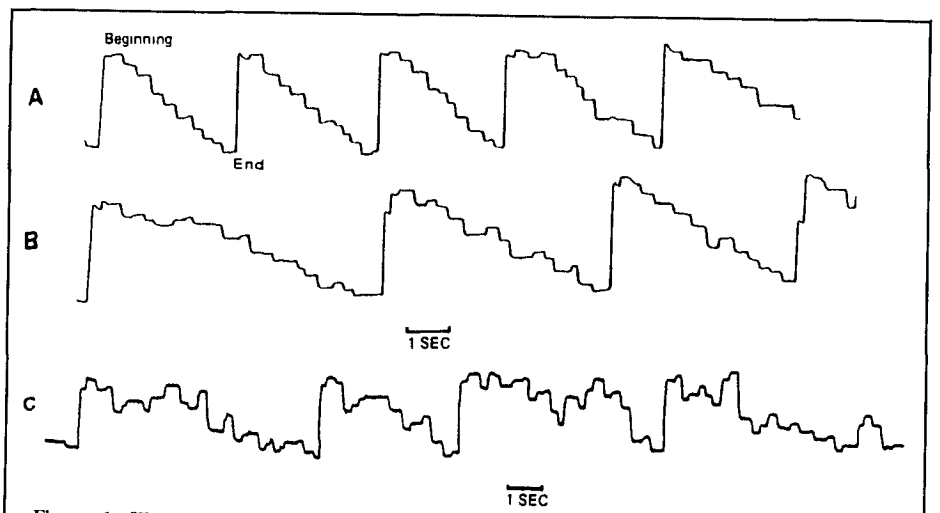

Figure 1. Illustrative eye movement records of regular L—R scanning of a normal reader (a) as well as a retarded reader (b), and the highly erratic patterns of a dyslexic (c) while reading text at their RA.

during the first three to four years of schooling. About two-thirds of the total development of readers' eye movements that occurs between the first grade and college level is achieved by 10 years of age (Taylor, et al., 1960). It is noteworthy that the EEG also starts to mature at about the same age (Epstein, 1980).

The overall developmental pattern for eye movements suggests that during both reading and visual search (Lloyd & Pavlidis, 1978a,b; Mackworth & Bruner, 1970; Vurpillot, 1976) an inverse relationship exists between age and duration of fixation, and the number of forward and regressive eye movements (i. e. the older the child the shorter the duration of fixation). Usually, a shorter fixation is an indication of faster information processing.

Regressions during reading have been partly attributed to the problems that the reader has in comprehending the material (Bayle, 1942; Hue, 1908), to large forward saccades (Anderson, 1937; Andriessen & DeVoogd, 1973), and to semantic control and inference making (Just & Carpenter, 1978).

ERRATIC EYE MOVEMENTS AND DYSLEXIA

There is a consensus of opinion among eye movement researchers that a high number of dyslexics exhibit erratic eye movements during reading. The main characteristics of erratic eye movements are the excessive numbers of eye movements, particularly regressions, which often occur two or more in succession. The sum of amplitudes or individual amplitudes of regressions can be larger than the proceeding forward saccade. This is very different from patterns shown by advanced, normal, and non-dyslexic retarded readers, who make singular regressions of the same or smaller size than the preceeding forward saccade.

Other characteristics of erratic eye movements include great variability in size and duration. The overall impression given by an erratic eye movement pattern is its irregularity, idiosyncratic shape, and the lack of a consistent repetitive pattern line after line. As seen in Figure 1, the pen recordings of normal and advanced readers' eye movement patterns resemble the shape of a staircase. Each "staircase" represents a line of text. The longer the time spent to read the line the longer the staircase. Its top "step" represents the first fixation at the beginning of the line, while the bottom "step" represents the last fixation at the end of the line. Forward eye movements (L-R) go from top to bottom, while regressions (R-L) have the reverse direction.

PLEASE PLACE FIGURE 1 ABOUT HERE — SLUG

Even mild eye movement disorders usually are accompanied by difficulties in maintaining fixation, holding the eyes on the same line, maintaining a sequential scanning of words or lines, and an inability to keep reading for more than a few minutes without feeling fatigued.

There are only a small number of eye movement studies of dyslexia during reading. In most of them, the subject selection criteria, as in other studies of dyslexia, have not been adequate. Most of the eye movement studies are either case studies (Ciuffreda et al., 1976; Elterman et al., 1980; Goldberg & Arnot, 1970; Pavlidis, 1978; Pirozzolo & Rayner, 1978; Zangwill & Blakemore, 1972) and/or they focused on isolated eye movement characteristics without any attempt for quantification (e. g. Elterman et al., 1980; Goldberg & Arnot, 1970). Only in a few studies have the eye movements of dyslexics and "matched" controls been compared and statistically analyzed (e.g. Gilbert, 1953; Griffin et al., 1974; Heiman & Ross, 1974; Lefton et al., 1978; Lesevre, 1964; 1968; Pavlidis, 1979, 1981b; Rubino & Minden, 1973.)

The first association between reading disability and wandering, irregular eye movements was made by Freeman (1920) and Gray (1921). Gilbert (1953), in his extensive study of the developmental relationship between eye movements and reading ability, found that subjects with reading difficulties made a much higher percentage of regressive eye movements than normal readers. Lesevre's (1964; 1968) results were similar to Gilbert's. Lesevre's results from reading and non-reading studies led her to the conclusion that the irregular eye movements of dyslexics could not be attributed to reading habits, poor teaching, or environmental factors.

In a less carefully controlled study, Rubino and Minden (1973) found that the LD children made significantly more fixations and regressions than the normal controls, but there were no significant differences in the duration of their fixations.

Similar results have also been reported by Griffin et al. (1974), who compared the eye movements of a heterogeneous group of 13 male "inadequate readers" with 13 normal control subjects during reading and non-reading tasks. During reading, the inadequate readers made significantly more fixations per line and had a shorter span of recognition than the normal readers.

One of the best known case studies of a dyslexic has been reported by Zangwill and Blakemore (1972). They recorded the eye movements of a 23-year-old dyslexic graduate student while he tried to read and found that his oral reading was slow and marked by occasional self-corrected misreadings and verbal transpositions. His spelling was bizarre and included omissions of individual letters and homophones. When he was younger, he was often reported to reverse words. His eye movements during reading were erratic with a strikingly large number of regressive movements. Sometimes, "he started from the right side of the line and made a perfect, fast series of flicks along the line from the right to left without a single 'regressive' movement in the correct direction" (p. 372). Zangwill and Blakemore attributed his erratic eye movements to an "irrepressible tendency to move his eyes from right to left rather than left to right" (p. 372). Therefore, they explained his reversals and transpositions in terms of his erratic eye movements. They further suggested that erratic eye movements "may not be a primary symptom in all dyslexic patients, but it may be in some, particularly those who show mixed laterality" (p. 373).

Although researchers agree that a number of dyslexics exhibit erratic eye movements during reading, they disagree on the extent and the nature of the relationship between erratic eye movements and dyslexia. A number of contradictory hypotheses have been put forward to explain the dyslexic's erratic eye movements during reading. These hypotheses can be grouped into three categories 1) erratic

eye movements are just another reflection of the problems dyslexics have with the reading material (Ellis & Miles, 1981; Goldberg & Arnot, 1970; Tinker, 1958); 2) erratic eye movements may sometimes cause dyslexia (Goldrich & Sedgwick, 1982; Griffin et al., 1974; Hildreth, 1963; Lesevre, 1964; 1968; Zangwill & Blakemore, 1972); and 3) erratic eye movements and dyslexia are the symptoms of one or more commonly shared or independent but parallel central deficits (Pavlidis, 1983c, in press a, b).

DIFFERENCES IN EYE MOVEMENT PATTERNS BETWEEN DYSLEXICS AND OTHER POOR READERS

If dyslexics' erratic eye movements are caused by bad reading habits or by the difficulty they have with the reading material, then they should have similar eye movement patterns to other equally poor readers who are not dyslexic. Similarly, when dyslexics read easy texts (one year below their reading level) their eye movements should be converted to regular "staircase" patterns because they have no difficulty with the text. Finally, normal readers' eye movements should become erratic or should make an excessive number of regressions when they read a difficult text (one year above their reading level).

In order to test these hypotheses, Pavlidis (1981b) conducted a study in which the eye movement patterns of dyslexics, other retarded readers, normal, and advanced readers were compared. In selecting the research diagnostic criteria for dyslexia, care was taken to exclude any known factors that could potentially be a primary cause of the reading problem. Another aim of the criteria was to quantify as many qualitative factors as possible, e. g. educational opportunities (Pavlidis, 1981b; in press, b).

Guided by these concepts, the following factors were taken into account in establishing the research diagnostic criteria for dyslexia. In summary, they were; average or above average I.Q., at least 1.5 years retarded in reading if below 10 years of age or 2 years reading retardation (in relation to their chronological age) if above 10 years of age, normal visual and auditory acuity, advantaged socioeconomic background, no emotional or motivational problems prior to beginning reading, no overt physical handicaps, adequate educational opportunities (e.g. lack of excessive absenteeism and frequent school changes) (Pavlidis, 1981b, 1983b, in press b). Children who fulfilled all these criteria were included in the dyslexic group. Among other factors, the control group of advanced and normal readers were matched to dyslexics for chronological age, while the retarded readers were matched for both chronological and reading ages (Pavlidis, 1981b, in press b).

While the children were reading, their horizontal and vertical eye movements were recorded by means of the highly sensitive, non-invasive photo-electric method, modified by the author to suit the experimental requirements. The sensitivity of the method was enough to distinguish fixations on different letters of the same word.

The analysis of the results of this study have shown that the number of forward and regressive eye movements was significantly higher in dyslexic than in the matched retarded, normal and advanced readers. These findings replicated our earlier study comparing dyslexics with matched normal readers (Pavlidis, 1979), and were also in agreement with the findings of the rest of the literature (Gilbert 1953; Lesevre, 1964; 1968).

The characteristic that again stood out was the excessive number of regressions made by dyslexics. In a number of cases, the dyslexics' regressions occurred in succession, in clusters of two or more, producing an irregular, erratic pattern as can be seen in Fig. 2.

Each square of Fig. 2 represents a page of text. The horizontal location of the numbers represents the position of the fixation in relation to the line, while the consecutive numbers reflect the order of their occurrence. The normal reader read each line with regular left to right eye movements, interrupted by small regressions. The dyslexic, however, made 41 disorganized eye movements to read one line and needed two large eye movements to reach the beginning of the next line.

To summarize the results, the dyslexics made significantly more regressive eye movements and fixations than each of the other three control groups, while each child read text appropriate to his/her reading age. Retarded readers made significantly more regressions than normal readers, and they in turn made significantly more than advanced readers. Dyslexics made significantly more regressions than the normal readers even when dyslexics read the easy text for them and the normal readers the difficult.

These results raise the following question: did the dyslexics simply make more eye movements than the other readers, and hence made more regressions, or did they also make different kinds of eye movements? To answer this question, the percentage of regressions of the total number of eye movements was compared. The dyslexics were still found to have significantly more regressions than other readers, including retarded readers (DF = 1,30, $p<.0008$), but there was no significant difference between the non-dyslexic groups. This finding suggests that the advanced, normal, and retarded readers belonged to the same continuum, while the dyslexics were a group of readers distinct from the retarded and other readers.

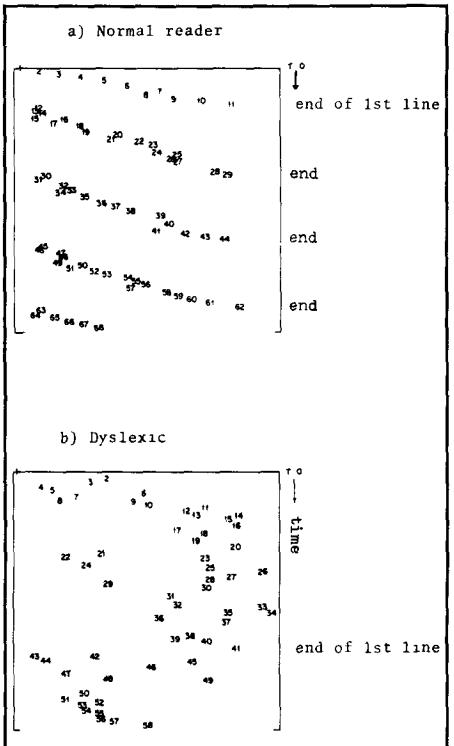

Figure 2. Computer produced eye-movement records of a normal reader (a) and a dyslexic (b) indicating the order of each fixation and its location in relation to the line of text.

On the basis of the results of this study, the first hypothesis which suggested that dyslexics' erratic eye movements are just the reflection of the problems they have with reading is rejected for two reasons. First, the eye movements of the dyslexics and the matched retarded readers should have been similar because they were equally retarded in reading. On the contrary, they were found to be significantly different. Second, the easy text did not "normalize" the dyslexics' eye movements. Further supporting evidence comes from the fact that the normal readers' eye movements did not become erratic even when they read a difficult text. The data show that: a) text difficulty can alter positively or negatively dyslexics' eye movement pattern and characteristics but only up to a point; and b) the erratic eye movements were not caused soley by the problems dyslexics had with reading. The results of this study do not support the hypothesis that erratic eye movements are caused by the problems only dyslexics have with reading. These studies, however, have yet to answer questions about the causes of the dyslexics' erratic eye movements.

ERRATIC EYE MOVEMENTS IN NON-READING STUDIES

By definition, dyslexia cannot be attributed to low I. Q., emotional, motivational, educational or environmental factors. So, the remaining plausible cause(s) can be brain malformation or malfunction. In this regard, the recent cytoarchitechtonic analysis of the brain of a dyslexic (Galaburda & Kemper, 1979) is important because it demonstrates that innate, but circumscribed malformations of the brain exist in dyslexics. Further studies of dyslexic brains have revealed similar malformations (Geschwind, 1982; Galaburda, in press). These malformations have been attributed by Geschwind (1982) to the period when the formation of the brain tissues occurs in the womb.

If dyslexia is caused by a brain malfunction, then such a malfunction should manifest itself not only during reading, but also during other tasks which depend on skills that are fundamental to the reading process and are processed by the same parts of the brain. Dyslexia might become a clearly identifiable category if dyslexics were found to also be significantly different from other readers (and especially matched retarded readers) in non-reading tasks that simulate the non-verbal aspects of the reading process.

One such attempt was made by Gilbert (1953), who tried to find out whether there was a correlation between eye movement efficiency and performance in reading and non-reading tasks. His 528 subjects included above-average, average, and very poor readers. The subjects' eye movements were photographed while they either read prose passages, or fixated on a series of digits, with the digits substituting for words. A strong inverse relationship was found between age and number of eye movements needed to fixate the digits. The older the child, the fewer eye movements they made. Regression proved to be the most sensitive index of the motor efficiency of the eyes. The correlations between frequency of regressions during prose and sequentially fixating digits were found to be high. Gilbert further stated that: "there was no instance of a pupil who was very superior in fixation frequency in reading prose and yet proved very inferior in fixation frequency in reading digits. Rather, the data are consistent in pointing out the fact that individuals whose eye movement behavior is most efficient in one type of reading show superiority in the other type also; and very inferior performance in either activity is generally predictive of inferior performance in the other type." (p. 203).

Similar results to Gilbert (1953) have been obtained in France by Lesevre (1964, 1968), who tested children between 5 and 12 years of age in a similar non-reading task. Younger children's eye movements were found to be inadequate. After the 7th year, however, their performance improved significantly and this improvement remained almost unchanged in adults. These findings suggest that maturation of the parts of the brain responsible for the sequential control of the saccadic, or possibly any other "sequential" system, may constitute a prerequisite for the accurate execution of any sequential task such as reading. It may not be accidental that worldwide, the start of schooling coincides with the period that the oculomotor system becomes mature enough for such tasks as reading.

Consistent results with Gilbert and Lesevre were also found by Griffin et al. (1974), who tested their subjects on four non-reading tasks consisting of sequentially fixating on equidistantly spaced pictures, dots and three-letter words. The subjects were instructed "to merely look at each configuration as in a reading situation." Griffin and his colleagues concluded that: "Inadequate readers seem to have less efficient saccadic eye movement regardless of the type of material used. While the inadequate readers were heterogeneous, two distinguishable categories at either end of the range of performance emerged. The first group sequenced saccadic eye movements too rapidly, skipping and omitting material. The second group sequenced saccades too slowly, resulting in overfixation" (p. 315). Their final conclusion was that "disorder of saccadic EMs is a problem of microsequencing." (p. 316).

Lefton, Lahey, and Stagg (1978) compared the eye movement strategies used by adults, normal, and dyslexic children while they tried to choose from one of four five-letter alternatives that matched a sample. Lefton and his colleagues found that when attention had to be maintained for more than 5 seconds, the eye movement search patterns of dyslexics became erratic, and error rates rose steeply. They concluded that the children's inaccuracies in this task were due to ". . . their unsystematic strategy in examining letters and their failure to use a positive systematic sequential examination under sustained attention" (p. 30).

Elterman et al. (1980) recorded the horizontal and vertical eye movements of five seven-year-old "dyslexics" and two normal readers, who were given a variety of reading and non-reading tasks. Unfortunately, the subject selection criteria were not given, four out of five "dyslexics" were on medication, and they only selectively reported some of the eye movement reading patterns. However, it is noteworthy that four out of five (80%) of their "dyslexics" showed some kind of sequencing oculomotor problem and erratic eye movements either during reading or non-reading tasks or during both. They concluded that for some dyslexics ". . . a primary eye movement abnormality may play a contributing role in some cases of developmental dyslexia." (p. 20)

Consistent with the finding of the previously mentioned studies were also the results of Goldrich and Sedgwick (1982) who recorded the eye movements of 15 normal and 16 reading disabled readers between 7-and 17-years-of-age while they scanned a variety of non-reading visual stimuli. They found that the reading disabled subjects differed significantly from the normal controls. Their conclusion was that "the findings support the idea that reduced oculo-motor control may be a significant factor in reading disability" (p. 59).

In an effort to explore further the possible correlates of erratic eye movements beyond reading, Pavlidis (1981a) compared 12 dyslexics and matched normal readers. They were tested in a non-reading task that simulated the sequential scanning from the beginning to the end of the line that occurs during reading. Words were replaced with lights. Children were asked to follow, as quickly and as accurately as possible, 5 lights that were equidistantly spaced in a horizontal array. They were illuminated sequentially and each stayed on for a second except that the two extreme lights stayed on for 2 seconds. The process started on the extreme left light and each lit up in turn until the extreme right light was lit, then the reverse sequence was completed. As they followed the lights, their eye movements were recorded.

Dyslexics made significantly more eye movements than the matched normal readers. Their most prominent difference was again found to be in the number of regressions (Pavlidis, 1981a).

Since this original study, a few studies were carried out using seemingly similar but essentially different testing procedures, stimuli, and subject selection criteria. So, the findings of these studies have been different. For instance, Stanley et al. (1983), Brown et al. (1983) and Olson et al. (1983) compared learning disabled readers of varying disability with matched normal readers. They did not find significant differences between the two groups. Pavlidis (1983a, in press a.) attributed the differing results to four factors on which these studies differed from the original: 1) subject selection criteria; 2) experimental procedures; 3) data analysis procedures; and, 4) temporo-spatial characteristics of the sequentially

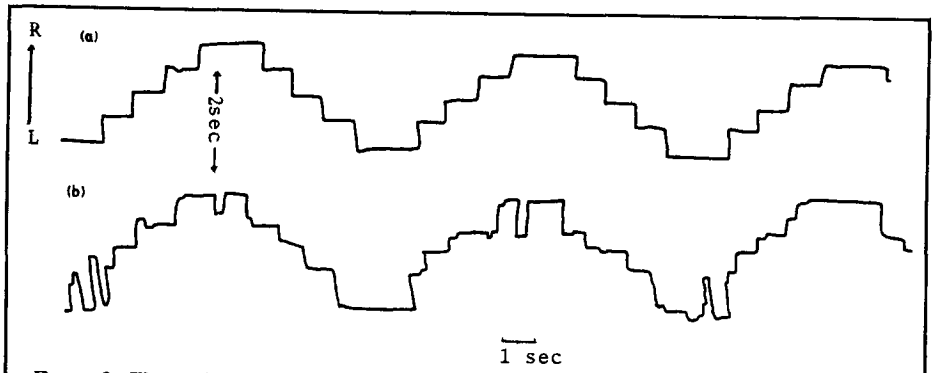

Figure 3. Illustrative normal eye-movement record of a 12-year-6-month-old normal reader with average I.Q. (a), and an erratic record of a 12-year-6-month-old severe dyslexic with I.Q. 120 (b) while following the sequentially illuminated lights from left to right and right to left.

illuminated lights. Pavlidis' original findings, however, have been supported by other studies in Europe and the United States (Cizek and Jost, 1984; Jerabek, 1984; and Mawson, 1984) and they have also been replicated in our own laboratory (Pavlidis, 1981b; 1983c). The results of these latter studies are also consistent with findings from other studies that have investigated eye movement patterns of dyslexics in other non-reading situations (Elterman et al., 1980; Gilbert, 1953; Goldrich & Sedgwick, 1982; Lesevre, 1964; 1968).

The results of the previous studies do not exclude the possibility that the dyslexics' erratic eye movements and high number of regressions are related to the problems they experience with reading and to possible bad scanning habits that may result from them. In order to explore this possibility, we carried out a study comparing dyslexics matched for reading and chronological ages to retarded readers. Although both groups experience similar difficulties in reading, the causes are assumed to be different. For dyslexics, the difficulties are attributed to brain malfunction, whereas for the retarded readers they are linked to psycho-environmental factors (e.g. absenteeism, frequent school changes, emotional instability, and adverse socioeconomic background). If, indeed, their reading problems are caused by different factors, then the two groups may exhibit different eye movement patterns and characteristics.

The same children that participated in our previously mentioned reading study also took part in this study. Dyslexics' eye movements were compared with those of matched advanced, normal and retarded readers. The children followed the same lights under the same conditions as in our study mentioned earlier (Pavlidis, 1981a). The results of the previous study comparing dyslexics and matched normal readers were replicated in this second study. As during reading, the most striking differences between dyslexics and all other groups of readers were found in the number of regressions. As can be seen in Fig. 3, unlike the normal reader, the dyslexic made many regressions and forward movements; similar to those he made while reading. It is noteworthy that the dyslexic boy made far more small adjusting eye movements and at least in the four out of five two-second fixations he broke them into smaller ones (concentration problems). His tendency to incorrectly anticipate the onset of the next light sharply contrasted to the normal reader's consistently accurate fixations of the lights.

Dyslexics and retarded readers had highly significant differences in almost all eye movement variables, whereas the performance of retarded readers was not significantly different from that of normal or advanced readers. There was little overlap between dyslexics and all other readers in the number of their regressions. As shown in Table 1, dyslexics made a similar percentage of regressions while following the sequentially illuminated lights as they did during reading the easy text. On the other hand, as expected, the percentage of regressions for retarded, advanced, and normal readers dropped significantly from reading to

TABLE 1
Percent of Regressions while reading and while following lights

Groups of Readers	% Regressions Reading at RA	% Regressions Following Lights
Dyslexics		
$\bar{X}$	34 0	29.9
SD	8.0	8.1
Retarded Readers		
$\bar{X}$	22.9	9.8
SD	8.3	10 0
Normal Readers		
$\bar{X}$	20.8	6.8
SD	6.8	9.4
Advanced Readers		
$\bar{X}$	18.0	8.4
SD	8.4	11 4

non-reading tasks because there is no high level information processing involved in the light-following task.

A discriminant analysis was used to reclassify children as dyslexic, retarded, normal, and advanced on the basis of the number of percentage of eye movements made while following the sequentially illuminated lights. The results of this classification were compared with the initial classification made on the basis of the exclusionary criteria mentioned earlier. The agreement between the two methods of classification was very high (93.2%) when the children were divided into groups of dyslexic and non-dyslexic readers.

These results suggest that dyslexics, unlike other non-dyslexic readers, have primary central problems independent from reading. The non-dyslexic groups were indistinguishable from each other on the basis of their eye movement characteristics. This suggests that the reading problems of most of our retarded readers are secondary to psycho-socio-educational factors.

It is noteworthy that a small percentage of retarded readers had "dyslexic like" eye movements and the discriminant analysis classified them as dyslexics. This important finding was expected, because some children classified as retarded readers on the basis of psycho-socio-educational factors can be dyslexics who also happened to have emotional problems, to come from adverse socioeconomic backgrounds, and to have a high level of absenteeism and/or to have experienced many school changes.

CONCLUDING REMARKS

Controversy often is a positive factor for the advancement of knowledge. Too much of it, however, can be taken as a sign of an immature science. Dyslexia has had a great deal of controversy over the years. It may be time to pinpoint the main sources of this controversy and then take the appropriate steps to reduce it. The main sources of controversy are the following: 1) the lack of a positive definition of dyslexia; 2) the lack of research diagnostic criteria for dyslexia (they have to be quantifiable and much stricter than the clinical ones); 3) the highly variable and inadequately described populations of the experimental and control groups; 4) the unspecified and sometimes questionable experimental procedures; and 5) the different standards employed for data analysis.

The adoption of well specified standards for the study of dyslexia will be a first positive move in the right direction. Such standards will allow a meaningful comparison of the results of the various studies, as they will help clarify *who* and *what* we study. Pavlidis (1983b), among others, has proposed a set of quantifiable research diagnostic criteria for dyslexic subjects and for their matched controls. The adoption of comprehensive quantifiable criteria could lead to the formation of more homogeneous groups, with less overlapping between them. This, in turn, can lead to a higher quality of research studies and "cleaner" and more directly applicable data. It will further facilitate the search for subtypes in dyslexia.

The main conclusions that can be drawn from the eye movement studies of dyslexia are the following:

1. The dyslexics' erratic eye movements found during reading are not solely caused by the problems they have with reading. In fact, they are relatively independent of the reading material.
2. The results of the non-reading tasks further demonstrate that the dyslexics' erratic eye movements are due to a brain malfunction(s) yet to be determined.
3. The comparison of dyslexics, advanced, normal and retarded readers shows that eye movement patterns and characteristics in the non-reading "lights" test can differentiate dyslexics from these groups of readers.

The results of non-reading tasks involving sequencing (Zurif & Carson, 1970) are in agreement with those obtained in the sequential non-reading eye movement studies previously reviewed. These results draw further support from recent neurological findings. Ojemann and his colleagues (Calvin & Ojemann, 1980; Ojemann & Mateer, 1979), using brain stimulation techniques, have found that rapid, nonverbal facial sequential movements, phoneme identification, reading, and naming share the "same" area of the language cortex. Hence, it is reasonable to expect that when one of these functions is disturbed, the others can be affected as well. These results support my view that language dysfunctions (Liberman, 1983) and rapid, automated-sequencing problems are frequently linked. It is thus possible that in many dyslexics, erratic eye movements and language problems can be the epiphenomena of the "same" or independent but parallel brain problems.

It is important, from the treatment point of view, to determine the causes of erratic eye movements (Pavlidis, in press a, b). For the diagnosis of dyslexia, however, it is not important to know whether erratic eye movements are the cause or the effect of dyslexia or if erratic eye movements and dyslexia share a common or independent but parallel cause. In all four cases, though in different ways, the erratic eye movements will be linked to dyslexia. It must be emphasized, however, that the knowledge of the causes of the dyslexics' erratic eye movements and their relation to dyslexia can lead both to a more effective diagnosis of dyslexia and also to the discovery of appropriate educational methods of treatment. At the very least, this knowledge would indicate which methods should not be used for the treatment of certain dyslexics.

The advantage of non-reading eye movement tasks is that they take only a few

minutes to administer and automatically analyze. The screening of whole school populations becomes feasible, and hence, the prevalence of dyslexia in the general population could be objectively assessed and accurately estimated. For such an estimation to be more accurate, the possible prevalence of erratic eye movements among neurologically impaired individuals, without reading problems, can also be established. It is also necessary to establish norms and the percentage of false positives and negatives. This study is already undertaken by the author.

A diagnostic test of dyslexia based on non-reading tasks is independent of reading skills, and thus, it may be used internationally even before reading age, if dyslexics' brain malfunctions exist before reading age. The limits of its predictive value could be determined by the outcome of developmental investigations of the development of the functions/skills under study and their relationship to reading achievements.

An early diagnosis of dyslexia is useful for a number of reasons. On the one hand, the earlier the diagnosis the greater the possibility of ensuring maximum advantage of the plasticity of the brain either by energizing its "dormant" circuits or by forming new ones through educational remediation or medication. On the other hand, early diagnosis will also increase the chances of ameliorating the debilitating educational and psychosocial consequences of dyslexia.

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