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What is This?

Role of Visual Attention in Cognitive Control of Oculomotor Readiness in Students with Reading Disabilities

Harold A. Solan, Steven Larson, John Shelley-Tremblay, Anthony Ficarra, and Michael Silverman

Abstract

This study investigated eye movement and comprehension therapy in Grade 6 children with reading disabilities (RD). Both order of therapy and type of therapy were examined. Furthermore, the implications of visual attention in ameliorating reading disability are discussed. Thirty-one students with RD were identified using standardized reading comprehension tests. Eye movements were analyzed objectively using an infra-red recording device. Reading scores of participating children were 0.5 to 1 *SD* below the national mean. Testing took place before the start of therapy (T1) and was repeated after 12 weeks (T2) and 24 weeks (T3) of therapy. One group of students had eye movement therapy first, followed by comprehension therapy; in the other group, the order was reversed. Data were evaluated using a repeated measures MANOVA and post hoc tests. At T1, mean reading grade was 2 years below grade level, and eye movement scores were at about Grade 2 level. Mean growth in reading comprehension for the total sample was 2.6 years ($p < .01$) at T3; equally significant improvement was measured in eye movements ($p < .01$). Learning rate in reading comprehension improved from 60% (T1) to 400% (T3). Although within-group differences were statistically significant, between-group differences were not significant for comprehension or eye movements. Order of therapy (comprehension first or eye movements first) was not significant. Improvements in within-group scores for comprehension and eye movements were consistently significant at T2 and T3. Eye movement therapy improved eye movements and also resulted in significant gains in reading comprehension. Comprehension therapy likewise produced improvement both in eye movement efficiency and in reading comprehension. The results support the notion of a cognitive link among visual attention, oculomotor readiness, and reading comprehension.

lthough there has been abundant research during the past 3 decades, the answer to the question "Why can't Johnnie read?" remains equivocal. The purpose of this article is to review some of the visual antecedents of reading disability (see Note 1) that are relevant to the current research, to report the results of a prospective therapeutic study that uses several of these principles in a population of sixth-grade children with reading disabilities (RD), and to operationalize visual attention (see Note 2) and consider its role in oculomotor readiness.

After a century of research, there is evidence that reading disabilities should be attributed to disordered verbal and phonological development (Galaburda, 1988; Vellutino, 1979) and visual dysfunctions. The latter include a combination of refractive (Grisham & Simons, 1986), binocular (Simons & Grisham, 1987), perceptual (Solan & Ficarra, 1990), and eye movement (Eden, Stein, Wood, & Wood, 1994) disorders that have been associated with poor reading efficiency. Although these functional visual disorders may be contributory, they can make it profoundly difficult for the child to respond effectively to classroom learning where the need to sustain effort visually at the reading distance for extended periods of time is paramount.

Literature Review

There is substantial evidence that the analysis and treatment of dyslexia is much more complicated than the unitary verbal model proposed by Vellutino (1979). For example, Eden, Stein, Wood, and Wood (1995) compared the performance of nondisabled readers (NR) and individuals with RD on phonological and visual tests. Predictably, NR performed better than RD on the phonemic awareness tests. The RD group's performance also was significantly poorer than the NR group on several visual and eye movement (EM) tests, such as dot localization, vertical tracking, fixation stability, and binocu-

lar divergence. These visual tasks were almost as useful as phonological tests in discriminating between NR and RD groups; 68% of the variations in reading of both the NR and the RD group could be predicted by combining the visual and phonological scores in a multiple regression analysis. Subsequently, Stein and Walsh (1997) reported evidence to support the concept that dyslexia is not exclusively the product of either phonological, visual, or motor deficits. Cognitive processing involving expressive, receptive, and oculomotor systems seems to be impaired.

Eden et al. (1994) also questioned the conventional wisdom that the underlying defect in the control of eye movements seen in RD is predominantly the result of language problems. Eye movement recordings were measured using nonverbal stimuli. The percentage of saccadic inaccuracies was significantly greater for individuals with RD than NR, and eye movement stability of children with RD was poorer at all levels of convergence. Oculomotor vergence amplitudes were lower for RD than NR. The investigators concluded that the prevalence of oculomotor abnormalities in nonreading tasks suggested that the underlying deficit in the control of eye movements observed in dyslexia is not caused solely by language problems (Note 3).

In addition to visual functional disorders, a complementary hypothesis that has generated significant research warrants appraisal. Reading disability has been associated with a slow rate of processing in the magnocellular visual pathway (Chase, 1996). The visual system comprises two interactive parallel pathways, magnocellular (M-cell) and parvocellular (P-cell), sometimes respectively identified as *transient* and *sustained*. The concept of dual processing has its roots in the anatomy and physiology of the visual pathways (Felleman & Van Essen, 1991; Gross, 1992; Livingstone, Rosen, Drislane, & Galaburda, 1991; Mishkin, 1972; Motter, 1991; Shapley, 1992) and has been corroborated functionally in psycho-

physical studies by Breitmeyer (1980, 1993), Lovegrove, Martin, and Slaghuis (1986), and Lehmkuhle, Garzia, Turner, et al. (1993). Williams, LeCluyse, and Rock-Faucheux (1992) and Solan, Brannan, Ficarra, and Byne (1997) reported relationships between wavelength, luminance, and reading performance. The results of using blue filters to reduce wavelength and gray filters to lower luminance improved reading comprehension significantly in poor but not in average readers, and suggested the presence of a magnocellular deficit.

Recent studies have used functional magnetic resonance imaging (fMRI) to measure brain activity in conditions designed to preferentially stimulate the M-cell pathway in individuals with and without RD. In individuals with RD only, fMRI testing provided an objective measure of abnormal processing of visual motion, especially in the extrastriate middle temporal (MT) brain areas, which have been identified as motion sensitive (Demb, Boynton, & Heeger, 1997, 1998; Eden, VanMeter, Rumsey, Maisog, et al., 1996). The results lend further support to the hypothesis of an M-cell pathway visual abnormality in RD. The pathophysiology of developmental dyslexia is more complex than originally thought, extending well beyond the classically defined language areas of the brain to the vision processing areas and the centers controlling eye movements (Eden & Zeffiro, 1996). The presence or absence of M-cell pathway deficits can also be ascertained using critical flicker fusion (CFF; Brannan & Williams, 1988; Martin & Lovegrove, 1987, 1988), visual evoked potentials (Brannan, Solan, Ficarra, & Ong, 1998; Lehmkuhle et al., 1993), and varying wavelength of stimulus (Solan, Brannan, et al., 1997; Solan, Ficarra, Brannan, & Rucker, 1998; Williams et al., 1992). The relationship of fixations and regressions to a possible M-cell deficit was especially evident in the Solan et al. (1998) study. These procedures can potentially provide clinicians who are engaged in the treatment of learning-related vision

disorders with the means to identify M-cell deficits and to assess the effects of their intervention with an independent index of therapeutic efficacy. At this juncture, it is reasonable to postulate that functional and temporal visual deficits may exist concurrently in the same individual, although specific research is lacking.

Steinman, Steinman, and Garzia (1998) investigated the spatiotemporal characteristics of visual attention in individuals with RD experimentally. They concluded that M-cell pathway deficits in reading disability are manifested as a visual attention abnormality with direct implications to the reading task. In individuals with RD, who in general are known to have reduced attention spans, this characteristic interferes with oculomotor processing as attention moves from word to word and from fovea to parafovea to fovea. In NR, when the loci of fixation and attention are coincident, visual tasks are performed more efficiently because the direction of gaze and the direction of attention are identical in space. This skill is called *voluntary attention* and is clinically trainable. Visual attention shifts within a fixation from the fixation point to the right parafoveal region (previewing), so that the next saccade may be programmed. Because perceptual attention cannot be fully dissociated from the goal of the saccade (Kowler, Anderson, Dosher, & Blaser, 1995), *oculomotor readiness* depends on the shift in visual attention that precedes executing refixation. Thus, attention drives the saccades. The lower spatial frequency in the parafoveal area serves as an M-cell pathway stimulant. That is, retinal images normally are sampled at least twice in the visual system, first by the M-cell then by the P-cell pathway.

During each fixation, the slower sustained system (P-cell) is activated and extracts the details of the text. It has a longer response persistence that may outlast the duration of the stimulus. When the M-cell and P-cell pathways are synchronized (as in NR), the motion on the retina generated by each

saccade inhibits the visual persistence from the previous fixation. The effect is to prevent the trailing persistence of the preceding sustained pattern from interfering with the current detailed information. M-cell pathways appear to control oculomotor efficiency in reading; therefore, any alteration of the normal order and timing of relative contributions or processing rates of the M-cell and P-cell pathways can result in a visual deficit (Breitmeyer, 1980, 1993).

The neural pathways that control eye movements have been well established. After entering the extrastriate cortex, the M-cell stream projects from MT to the posterior parietal cortex (PPC). The cortical regions to which it projects are involved in the control of spatial attention and eye movements. PPC serves as a bridge to the frontal eye fields (FEF) that are of crucial importance for the initiation of purposive saccadic eye movements, in the sense that they act as a selector of ocular strategies (Fischer & Boch, 1991). Other higher level sites that influence saccadic pulse generation include thalamus (dLGN), posterior parietal cortex, frontal eye fields, and superior colliculus, the latter serving as a saccadic encoding nucleus (Ciuffreda & Tannen, 1995). These regions are recipients of dense noradrenergic (NA) innervation, which constitutes a neuroanatomical system that regulates attention (Halperin, 1996).

However, reduced visual attention in RD decreases the magnitude of the stimulus to the transient system. This delay interferes with the normal timing of the transient–sustained synchronization. Diverting attention slows processing by reducing firing rates, which increases the transient response latency. The prior fixation's persistent neural image at the fovea is not suppressed, and the resulting superimposition may cause retinal image smear that is manifested as noise in the cognitive system. Failure of visual attention to shift from the fixation point to the right parafoveal region with subsequent refixation represents an M-cell

dysfunction. As attention guides saccades, the link between shifts in spatial attention and the generation of saccadic eye movements is absent (Clark, 1999). Thus, individuals with RD frequently present with an excessive number of fixations and regressions, an indication that oculomotor fluency has been compromised. Abnormal patterns of saccadic reaction times observed in RD (increased transient latencies) reflect defects in the system of visual attention or in its control over the oculomotor system, rather than indicating a defect in the oculomotor system itself. Reading disability is thus manifested as a combination of attentional deficits and irregular timing of saccadic eye movements, resulting in EM patterns that are erratic, show excessive regressions, and have greater irregularity in saccade lengths and fixation durations (Biscaldi & Fischer, 1994; Fischer & Weber, 1990). Abundant evidence supports the notion that, during complex visual tasks such as reading, a functional relationship exists among M-cell pathway, allocation of visual attention, and overt eye movements (Henderson, 1992).

Rayner (1995) has summarized the process of reading and eye movements by addressing five principal issues:

1. The span of effective vision;
2. Integration of information across eye movements;
3. Eye movement control (where to fixate);
4. Eye movement control (when to move);
5. Models of eye movement control.

His research confirmed that the perceptual span—the amount of information that the reader acquires in each fixation—is asymmetrical, extending 14 to 15 characters to the right as compared to 4 to the left. As the foveal area of clear vision is about 2 degrees, the word identification area is limited to about 7 letter characters. Therefore, the word identification span is smaller than the total span of vision. The average span of perception can be deter-

mined by computing the number of words per fixation. It is not fixed, but can be influenced by word length and vocabulary. Furthermore, because reading is developmental, in NR we expect the span to increase with age as the number of fixations decreases.
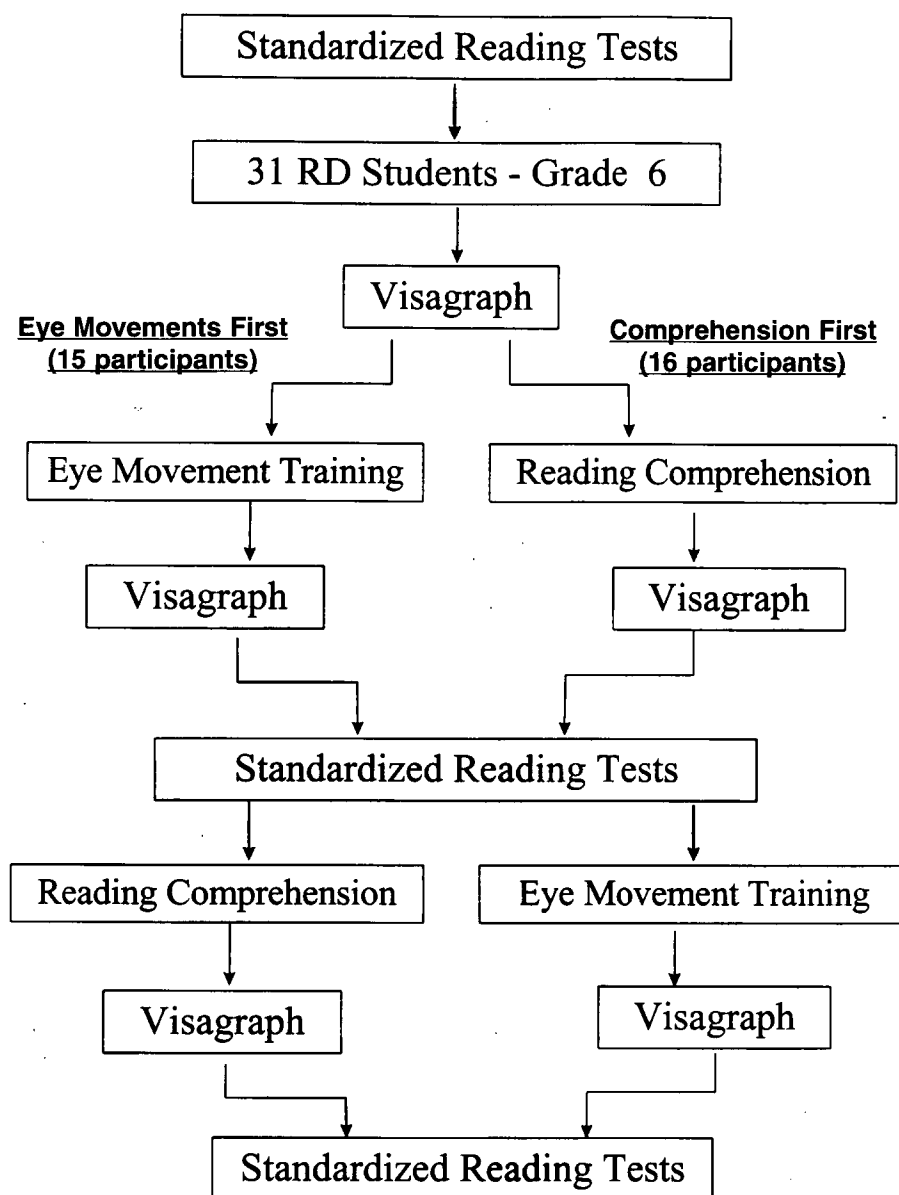
Study Purpose

In this article, we view reading disability as a cognitive deficit resulting, in part, from a neurobiological impairment. We were especially interested in quantifying the reading characteristics of a specific population of children with RD entering sixth grade, who averaged a delay of about 2 years in reading comprehension and obtaining a measure of their functional plasticity. The sequence of diagnostic tests and therapeutic interventions used is presented in Figure 1. Answers to the following questions were sought:

1. What is the relative value of training eye movements alone as compared to stressing comprehension alone (type of training)?
2. Is the sequence of training important? Will the improvement in reading comprehension be greater when eye movements are trained first followed by comprehension, or the reverse (order of training)?
3. If there is no difference between groups, are the within-group improvements statistically significant?
4. If there is no significant ordinal effect, what other factor (e.g., attention) do the two procedures have in common?

METHOD

Participants

Approximately 150 sixth-grade students (mean age = 11.4 ± 0.4 yrs.) attending general education classes in two neighborhood elementary schools were evaluated with the comprehension subtest of the Gates-MacGinitie

FIGURE 1. Factorial crossover design of the between-group and within-group organization of the study.

and parents were notified. Informed consent was obtained from the parents and from each child.

Procedures

Eye Movement Analysis. Eye movements were measured objectively using the Taylor Visagraph II (see Notes 5 and 6), an infrared computerized recording system. Each of the 31 participants read three 100-word, Level 4 selections from the Visagraph II reading selection book initially and answered ten comprehension questions from memory. The first selection, to validate the reading level, was read without goggles; the second selection, read with the infrared sensitive goggles but not recorded, familiarized the subject with the feel of the goggles; and the third, with goggles in place, was recorded. If fewer than seven questions were answered correctly in any selection, an additional trial was administered, but this was rare because the participants were reading at their independent reading level. The Visagraph II recordings provided objective baselines of each participant's reading eye movements: fixations and regressions per 100 words, and rate of reading with comprehension in words per minute. Because the average span of recognition (words per fixation) is the reciprocal of the number of fixations, this measurement has been omitted. The comprehension scores were automatically computed.

Therapy. The 31 participants were divided into two groups with approximately matched Gates-MacGinitie comprehension scores. All training took place using computer programs in each school. Half of the participants were provided with individual reading comprehension therapy first, whereas the other half received individual eye movement therapy, which stressed temporal processing, for 12 one-hour sessions. Comprehension therapy was equally divided between cloze (see Note 6) techniques, which required the participants to provide the

Reading Test (Level 5/6, Form K), carefully adhering to the recommended time limits. The schools served a mixed lower middle class population consisting of Caucasian, Asian, Hispanic, and African American children. For the purpose of this study, students with RD were identified as those scoring 0.5 SD to 1.0 SD below national means, equivalent to a range between the 31st and 16th percentiles ($M = 23.0$, $SD = 5.9$; see Note 4). This range of scores identified a sample of 31 students with

RD (about 20%), whose comprehension was approximately 1½ to 3½ years below grade level, grade equivalent (GE) 2.7 to 4.6 ($M = 4.1$, $SD = 0.43$). All of the children attended general education classes. Most had had the benefit of prior individualized supplementary help in reading, although the results had not been especially rewarding. A visual screening for acuity at far and near, hyperopia, near point phorias, and binocular fusion identified 5 children with visual disorders,

correct missing word(s) in a sentence, and reading selections, which were followed by detail, inference, reasoning, and main idea questions. Eye movement and speed of visual processing therapy, on the other hand, included PAVE (Perceptual Accuracy–Visual Efficiency) and Guided Reading (see Note 6). PAVE required participants to count the appearances of a particular digit or letter while following a left-to-right sequential presentation of three equally spaced characters per line on the screen, starting at 40 lines per minute and ultimately reaching 120 lines per minute (fixation duration about 150 ms). The Guided Reader used a moving left-to-right horizontal aperture that exposed three words at a time. By guiding the participants' eye movements across the screen continually as a high-interest story was read, reading rate and visual attention improved. All reading therapy was initiated at the participants' independent reading level as determined by the Gates-MacGinitie Reading Tests. Correctly answering 7 out of 10 comprehension questions at the end of each selection verified that the participant had indeed read and understood the story. Because the participants were individually monitored, it was possible to expose them to limited use of cognitive strategies. Immediate feedback to the participants was provided to encourage intrinsic motivation. They also learned the value of allocating processing resources to relevant stimuli. Equally important, they learned that the ability to inhibit responding to irrelevant stimuli was an important function of the information processing system (Sergeant, 1996). Over time, reading fluency and comprehension improved as the reading level and presentation rates in PAVE, Guided Reading, and specific comprehension therapy were gradually increased.

After the first 12 training sessions, an alternate form of the Gates-MacGinitie Comprehension Test (Form L), followed by one practice and one recorded Visagraph II test using different reading selections, were administered.

The eye movement and comprehension training groups were reversed in a crossover design (see Figure 1) for the next 12 sessions. After each participant had completed 24 sessions of eye movement and reading comprehension therapy, the Visagraph II and Gates-MacGinitie tests (Form K) were repeated for a third time, seven months after the original testing.

Data Analysis

The statistical analyses in response to two experimental conditions and five dependent variables were performed using a repeated measure analysis of variance (MANOVA) design (see Table 1). Order of therapy—eye movement therapy first or comprehension therapy first—are between-group conditions, and reading comprehension, learning rate, fixations, regressions, and reading rate are within-group variables in this crossover factorial design. The Tukey test for multiple comparisons was used to identify significant differences. Power and effect size were computed.

Results

A multivariate analysis of variance was performed with order of training as the between-group factor, and reading comprehension score, learning rate, number of fixations and regressions, and reading rate as within-group

factors. There was no significant main effect for order of training ($p = .641$), nor was there a significant interaction between order and training ($p = .953$). Observed power was .074, with a corresponding low effect size. Prior to therapy at T1 (see Table 2), there were no significant between-group differences in Gates-MacGinitie Reading Tests. The average grade equivalent (GE) for the 31 participants was 4.1, although they were entering Grade 6. If we presume mean comprehension scores entering Grade 1 were GE 1.1, which, after 5 years of school, showed 3 years of reading improvement (GE 4.1), the learning rate (LR) initially was .6 or 60%. The MANOVA revealed significant within-group main effects for all five dependent variables ($p < .01$): Gates-MacGinitie Reading Tests, learning rate, fixations, regressions, and rate of reading (see Table 1). Fixations and regressions per 100 words are closely associated with visual attention. Within-group improvements from therapy at 12 and 24 weeks (T2 and T3) are reported in Table 2. Significance levels were obtained with Tukey post hoc tests for multiple comparisons. Although there were no significant differences in between-group scores at T1, T2, or T3, after 12 weeks of therapy, within-group scores for comprehension first and eye movement therapy first improved significantly on the Gates-MacGinitie Reading Tests (see Table 2). After the crossover in therapy (see Figure 1), within-group scores continued

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TABLE 1
Multivariate Analysis of Variance (MANOVA) Results for Dependent Variables

Variable	SS	df	MS	F
Gates-MacGinitie	107.86	2	53.93	39.526**
Learning rate	2106.916	2	1053.458	6.345**
Fixations	38261.55	2	19130.75	30.391**
Regressions	3951.75	2	1975.88	14.299**
Rate of reading	38428.18	2	19214.09	26.348**

Note. Between-group effects were not significant. Only within-group main effects are shown.
**$p < .01$.

to improve significantly ($p < .01$) for the final 12 weeks. There was no interaction between order and training on the Gates-MacGinitie Reading Tests. Observed power was .057, with a low effect size. Within-group effects of training on fixations, regressions, rate of reading, and on the Gates-MacGinitie Reading Test each yielded an observed power equal to 1.00, with corresponding large effect size. Power and effect size exceeded the .8 level for an alpha of .05.

Of particular interest was the dramatic change in the participants' rate of learning to read. Table 2 compares the participants who received comprehension therapy first with those who completed eye movement therapy first. Learning rate (LR) is determined by GE change (in years) divided by the elapsed time in years (10 months equals a school year). Participants who received comprehension therapy first

showed an initial LR of 58%. Twelve weeks (.35 years) of comprehension therapy resulted in an improved GE of 1.3 years, a LR of 371% ($p < .01$). Subsequent eye movement therapy for 12 weeks resulted in an additional 1.3 years increment in GE, which equates to a total LR (T1–T3) of 371% or 2.6 years ($p < .01$) in 7 months.

Eye movement therapy prior to comprehension therapy yielded comparable outcomes (see Table 2). Initial LR was 62%, not significantly different from the participants who received comprehension therapy first. Twelve weeks of eye movement training produced 1.20 years improvement in GE, equivalent to a LR of 343% ($p < .01$). Comprehension therapy that followed resulted in a 1.5 year growth in GE, corresponding to a LR of 429% ($p < .01$). The average LR (T1–T3) for the students who received eye movement therapy first was 386% ($p < .01$), a

2.7 year reading comprehension growth in 24 weeks of therapy. Although within-group improvements were consistent, no significant statistical differences were noted between the two groups at crossover time (T2) nor after 24 weeks (T3). There was no therapeutic advantage to having either eye movement therapy prior to comprehension therapy or the reverse.

Significant within-group improvements in oculomotor efficiency as measured with Visagraph II resulted from eye movement and comprehension therapy. Table 1 lists the within-group main effects of five dependent variables: Gates-MacGinitie Reading Tests, learning rate, fixations, regressions, and rate of reading. All within-group findings show significant improvement ($p < .01$). Table 2 lists T1–T2, T2–T3, and T1–T3 Tukey post hoc multiple comparison results for each oculomotor variable taking into account

TABLE 2
Comparison of Comprehension Therapy First and Eye Movement Therapy First Group Outcomes at T1, T2, and T3

Dependent variable/Time	CTF[a]			EMTF[b]			Significance
	M	*SE*	*GE*	*M*	*SE*	*GE*	
Gates-MacGinitie (%ile)							
T1	**22**	**1.4**	**4.0**	24	1.5	4.2	$F(1, 29) = .222$, *ns*
T2	**37**	4.5	5.3	37	4.7	5.4	T1–T2**
T3	**51**	4.6	6.6	53	4.8	6.9	T2–T3**, T1–T3**
Learning rate (%)							
T1	**58**		4.0	62		4.2	$F(1, 29) = .222$, *ns*
T2	**371**		5.3	343		5.4	T1–T2**
T3	**371**		6.6	429		6.9	T2–T3**, T1–T3**
Fixations (per 100 words)							
T1	193.1	11.0	2	173.9	11.4	2	$F(1, 29) = .509$, *ns*
T2	151.4	11.8	3	148.9	12.1	3	T1–T2**
T3	137.9	7.9	4	132.0	8.2	5	T2–T3*, T1–T3**
Regressions (per 100 words)							
T1	44.1	5.1	2	39.6	5.3	2	$F(1, 29) = .327$, *ns*
T2	31.9	4.0	3	31.4	4.2	4	T1–T2**
T3	27.8	3.1	5	24.4	3.2	6	T2–T3*, T1–T3**
Rate of reading (words per minute)							
T1	111.6	7.4	2	113.8	7.6	2	$F(1, 29) = .056$, *ns*
T2	145.2	12.3	3	146.8	12.7	3	T1–T2**
T3	158.5	12.6	4	164.3	13.0	4	T2–T3*, T1–T3**

Note. CTF = comprehension therapy first group, $n = 16$. EMTF = eye movement therapy first group, $n = 15$. GE = grade equivalent.
*$p < .05$. **$p < .01$.

the two conditions—eye movement therapy first or comprehension therapy first. The results of this therapy program imply that either condition influenced reading comprehension equally in this sample. For example, the number of fixations (per 100 words) decreased significantly and grade equivalents increased regardless of whether eye movement therapy or comprehension therapy was administered in the first 12 weeks ($p < .01$). Similar patterns of improvement in reduction in number of regressions (per 100 words) and increase in reading rate (words per minute; $p < .01$) are cited in Table 2.

Although eye movement data revealed significant within-group improvements at T2 and T3, comparing the order of therapy produced no significant between-group differences. The correlation matrix showed that significant intercorrelations among fixations, regressions, and rate of reading ($p < .01$) occurred concurrently with oculomotor efficiency (see Figure 2).

Nevertheless, eye movement skills did not correlate significantly with Gates-MacGinitie reading comprehension scores at T1, T2, or T3. The small sample size, restricted range of reading scores, and relative brevity of the period during which therapy was administered probably contributed to this outcome. Finally, it is especially revealing to compare the minimal number of participants with uncorrected visual acuity and visual functional disorders in the visual screening to the initial 4-year lag in eye movement efficiency reported in Table 2. Good visual functioning implies the ability to read and study comfortably for extended periods of time; eye movements are a measure of the students' reading efficiency. It is possible that, when students reach Grade 6, annual school visual screenings have identified most individuals who require routine vision care. Oculomotor efficiency is not usually a component of vision screenings, and, therefore, deficiencies often remain undetected.

Discussion

To appreciate fully the implications of this study, it is necessary to be aware of the academic histories and demographics of the participants. We must recognize that they represent the reality of urban populations, as exemplified by the commonality of academic achievement level in reading. Participants selected for the research scored initially between the 16th and 31st percentiles on the standardized reading tests, which represented a grade equivalent (GE) range of 2.7 to 4.6. All were currently attending Grade 6, and most were capable of applying most elementary grade reading skills. Reading comprehension test scores revealed no significant difference between participants at the two schools. National origins, cultural backgrounds, languages spoken at home, and educational histories were heterogeneous. Some of the children were beneficiaries of social promotion and had experienced only modest academic successes in spite of prior individualized tutoring. At the start of the program, some appeared to be translating the reading selections into their native language. There were deferent participants who were compliant and easy to mold, whereas others had to be cajoled into full participation. With few exceptions, as the participants became more aware of their increasing mastery of their reading skills, these problems gradually became less egregious.

Of special interest are the improvements in reading comprehension that resulted from eye movement therapy alone as well as the further improvements in comprehension when eye movement therapy followed comprehension therapy. It is fair to say that some of the results reported are counterintuitive. Whereas one would expect comprehension therapy to improve reading comprehension significantly, the significant comprehension improvements resulting from eye movement therapy were not as predictable. The overall results (T3) confirmed that

improvement in reading comprehension was not solely a function of order of therapy or type of therapy. At T2 and T3, within-group improvements were significant with *either* type of intervention, but there were no significant between-group differences in comprehension.

The meaningfulness of this study becomes more appreciable when the changes in learning rates before and after therapy are considered. Learning rate represents the rate of growth in reading skills in a given time period. LR for the two groups—comprehension therapy first and eye movement therapy first—averaged 60% during the 5 years preceding the study, and there was no significant difference between the two groups. After 12 weeks of therapy, LR for comprehension therapy first improved to 371%, compared to 343% for eye movement therapy first. After the crossover, eye movement therapy yielded 371% growth, and comprehension therapy provided an LR of 429%. Although the average within-group LR showed impressive and meaningful progress, the order of therapy did not result in significant performance differences between the two groups in learning to read. The need for a control group was considered. First, the ethical dilemma precluded withholding therapy from a group of children with disabilities who, according to pretrials, would probably profit significantly from the intervention. Second, the participants' learning rate during the first 5 years of school (60%) was so poor, despite supplementary instruction, that it was unlikely a spontaneous reversal in learning would occur. Finally, the study was designed to include ordinal effects of two complementary approaches of reading improvement.

Previously reported research has differentiated between oculomotor efficiency of students with and without RD similar to those who participated in this study (Solan et al., 1998). Even when the linguistic demands placed on students with RD had been lowered to
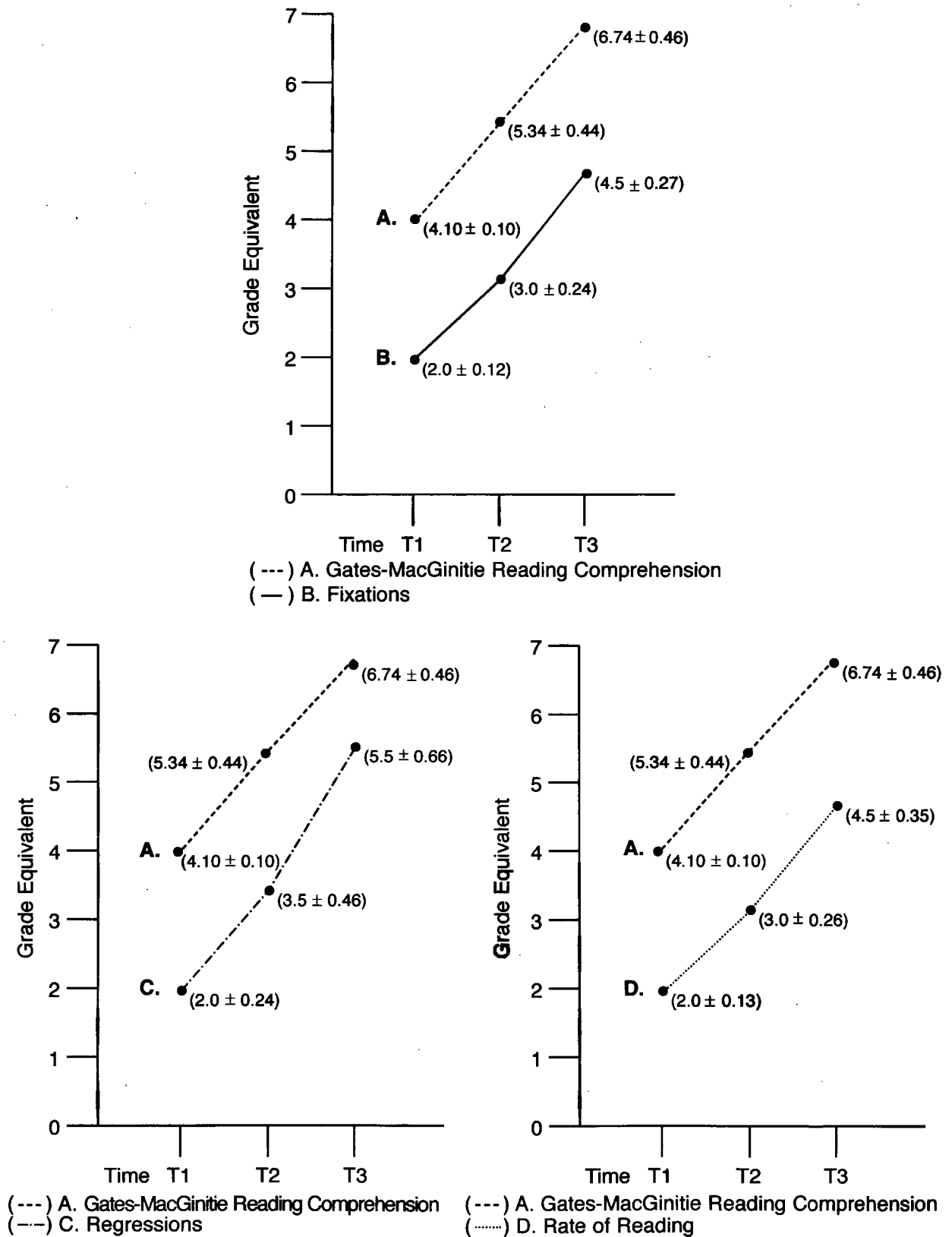
FIGURE 2. Improvement in reading comprehension compared to fixations, regressions, and rate of reading measured in grade equivalents at three time periods (Initial, 12 weeks, 24 weeks).

reading at their independent reading level in order to maintain 80% comprehension on the Visagraph II, a statistically significant difference in fixations, regressions, and rate of reading favored the NR group compared to the RD group. Removing the language differential alone did not alleviate the oculomotor deficiencies in children with RD. In the current study, within-group reductions in fixations and regressions and an increase in rate of reading at T2 and T3 were significant wether eye movements or comprehension were trained first. In the latter case, improved reading fluency apparently had a significant effect on eye movements. The combination of eye movement and comprehension therapy (T1 through T3) improved oculomotor efficiency regardless of the order of therapy, although no between-group statistically significant differences were observed. Finally, it was not possible to predict changes in reading comprehension from improvements in the oculomotor skills (see Figure 2).

Consistent within-group improvements in reading comprehension, learning rate, and oculomotor skills reflect the intensity of the therapy and the individual monitoring of participants throughout the study. The absence of significant between-group differences leaves several questions concerning the outcome of therapy unanswered:

1. Why didn't the eye movement therapy first group have better oculomotor skills than the comprehension therapy first group at T2?
2. Conversely, why didn't the comprehension therapy first group show greater improvement in comprehension than the eye movement therapy first group at T2?
3. Why didn't the order of therapy result in a significant difference in the outcome at T3?
4. Why didn't the basic eye movement efficiency components—fixation, regression, and rate of reading—significantly

correlate with reading comprehension in either group after therapy?

The significant within-group growth in reading and eye movement skills combined with the absence of between-group differences suggest that the two therapeutic procedures—eye movement and comprehension—may have been influenced by a catalyst common to both, such as *visual attention*. Limited attention span is a characteristic that is frequently associated with children who have been identified with a specific reading disability (American Psychiatric Association, 1994). Many children who have been diagnosed with attention-deficit disorder with or without hyperactivity also have reading disabilities. In either case, the impact of attention on cognitive efficiency and learning to read is considerable. Almost all measures of attention appear to represent a blending of various perceptual and cognitive abilities. Therefore, some children may perform poorly on a reported attentional task, not because their attentional system per se is deficient, but because one or more of their perceptual, memory, or executive functions (cognitive strategies) are deficient (Morris, 1996). Steinman et al. (1998) stressed the notion that attention drives the saccades. Whether they are mediated by the same neural circuitry or not, saccades and visual attention appear to be mutually interdependent. Fortunately, these results lend credence to the notion that it is possible to nurture some of the basic elements of both with training. This study supports the interaction among lexical development, eye movements, and attention. Because it was evident that, as a group, participants' perceptual sensitivity declined with time on task, it was necessary for each therapeutic procedure to include strategies to enhance attention. It was imperative to stress

1. screening out irrelevant stimuli;
2. maintaining performance and attention;

3. holding information in mind for brief periods.

Visual attention is a multidimensional trait that involves arousal, activation, and vigilance. We learned from this study that visual attention is malleable and can be modified.

To engage the participants' attention early in the therapy process, a special effort was made to create a success-oriented program. Because most of the participants had little history in experiencing success, teaching them to become sensitive to their own increasing mastery of the therapeutic encounters was a priority. Furthermore, improvement in intrinsic motivation appeared to have a salutary effect on sustaining attention. The PAVE and Guided Reading programs were especially suited to meet this need while simultaneously directing accurate attention to a specific location in the visual field. The moving stimuli also were helpful to maintain attention, improve short-term memory, and suppress irrelevant information that originated outside the field (Steinman, Steinman, Garzia, & Lehmkuhle, 1996). The PAVE program incorporates an automatic increase in the rate at which 3 different numbers or letters skip across the screen as a participant's saccadic and processing skills improve. When this rate reaches 60 lines per minute (1 line per second), 3 characters per second are being processed, and, therefore, processing time is about 0.3 seconds per character including time for interfixation saccades. As most subjects reached a saccadic rate of 120 lines per minute, processing speed was considerably faster than the fixation duration of a good reader. By developing a rapid systematic reading gait, reinforcing perceptual accuracy, and reducing processing time, PAVE therapy enhances visual attention. Guided Reading, which operates at a higher cognitive level, creates the opportunity to shift visual attention from the fovea to the parafoveal area to the right and refixate. The moving aperture functionally promotes a reduction in the number of fixations,

longer saccades, and an enlarged perception span. Perceptual span mediates the phenomenon of parafoveal preview, thereby facilitating the subsequent recognition of the parafoveal words. The latter is important because of the role of the right parafoveal area in oculomotor readiness. In both procedures, PAVE and Guided Reading, visual reaction times for detecting stimuli are reduced, so that attended targets are detected and processed faster and more accurately. Finally, making a precise return sweep from the end of one line to the beginning of the next has a positive effect on attention.

It would be inaccurate to create an artificial dichotomy between children with RD with lexical disorders and those with inefficient eye movements. By definition, most children with RD have some kind of language deficit, which could be either the cause or the effect of a poor eye movement pattern. In this study, vocabulary was reviewed prior to reading a comprehension or cloze selection. After reading 2 or 3 screens on the computer at a rate comparable to that used with the Guided Reader, various main idea, detail, reasoning, and inference questions were presented. In both comprehension programs, the combined effects of individual support and intrinsic motivation contributed to improved attention and eye movement efficiency.

The data support the reciprocal nature of the prime conditioners: eye movement proficiency, visual attention, and lexical development. Just as the development of reading comprehension skills improved both reading fluency and eye movement efficiency, the cumulative effects of specific oculomotor therapy, combined with Guided Reading, rapid visual processing, and heightened attention, benefited not only oculomotor efficiency but also reading comprehension skills.

Conclusions

In each individual, reading involves two distinct, albeit complementary, sets of processing: perceptual–attentional processing, which makes visual information available, and cognitive processing, which uses the information in reading (McConkie, Reddix, & Zola, 1992). The data presented by Rayner (1995) lend strong support for the complementary nature of

1. ongoing comprehension processing and the effect of lexical/cognitive development on eye movements; and
2. the effect of eye movement efficiency (oculomotor readiness) therapy on the process of reading.

The statistically significant within-group improvements in this study, as compared to the nonsignificant between-group outcomes at T2 in Table 2, imply that eye movement therapy affects comprehension and comprehension therapy affects eye movements. As each participant progresses in therapy, the meeting point between perceptual and cognitive processes varies, and visual perceptual input that is available to cognitive processing increases. Hoffman and Subramaniam (1995) suggested a link between attention and saccadic eye movements that reinforces the concept of oculomotor readiness. They proposed that readers first attend to a location before they move their eyes to it. Oculomotor readiness, sometimes called the *premotor theory of attention*, holds that movements of attention depend on the activation of brain structures that are intimately involved in moving the eyes. When participants move their eyes to a location in space, they attend to that location prior to the saccade. The current study reinforces the role of visual attention in the maturation of oculomotor readiness.

The authors agree with Rayner (1995) that

there is very good reason to believe that a model of eye movement control that allows for lexical processing to be involved in the decision about when to move the eyes is to be preferred over models that do not . . . I would like to make it clear

that by arguing for models of eye movement control that involve lexical processes in the decision to move the eyes, I do not mean to demean the results that have emerged from researchers interested mostly in the oculomotor aspects of reading . . . The issue is really one of emphasis. (p. 17)

The current study supports this notion, with the addendum that it acknowledges the central role of visual attention and its concomitant, visual memory, as the link with cognitive strategies and mental processes in reading. Finally, the three-digit improvements in learning rate demonstrated by these young students lend credence to the view that, even in less than ideal circumstances, it is possible to draw upon a significant degree of latent ability.

ABOUT THE AUTHORS

Harold A. Solan, OD, MA, is a distinguished service professor at the State College of Optometry, State University of New York. Current research interests stress the identification and treatment of magnocellular, oculomotor, and attentional deficits in the visual systems of children identified with reading disabilities. Steven Larson, OD, is an assistant clinical professor at the State College of Optometry, State University of New York. He is currently involved in treating children in the Learning Disabilities Unit who have reading or learning disabilities and who have significant visual processing, intersensory, and sensorimotor deficits. John Shelly-Tremblay, MA, is a graduate student at City University of New York, where he is working toward a PhD in experimental cognitive psychology. His thesis topic is event-related potentials in language processing. Anthony Ficarra, OD, associate professor and Chief of the Pediatric Optometry and Binocular Vision Service at the College of Optometry, Nova Southeastern University, served as statistical consultant. He is conducting research in visual factors in decoding. Michael Silverman, MA, is a graduate student at New School University, where he is completing his PhD degree in cognitive experimental psychology and conducting research in perception and cognition. His prior experience in counseling is a valuable asset in planning and evaluating therapeutic strategies. Address: Harold A. Solan, State College of Optometry/SUNY, 100 East 24th Street, New York, NY 10010 (e-mail: hsolan@sunyopt.edu).

NOTES

1. *In this article,* reading disability *represents a population with significant and unexpected difficulties in learning to read in spite of average intelligence and abundant educational opportunities.*

2. *We defined* attention *clinically as an integral member of the basic learning triad that also includes memory and information processing.* Visual attention *is defined as the selective use of information from one region of the visual field at the expense of other regions of the visual field.*

3. *See Solan et al., 1998. Even when the children with RD read selections at their independent reading level with an average of 80% comprehension, eye movements were significantly poorer than for NR with similar comprehension.*

4. *Children who score below the 16th percentile are more likely to have significant decoding problems that would not fit the experimental model of this study.*

5. *Average reliability (r_{tt}) of eye movement recordings for all components is about .90, comparable to most silent reading comprehension tests (unpublished study).*

6. *Related technical information and procedures are available from Taylor Associates/Communications, Inc., 200-2 East 2nd Street, Huntington, NY 11746.*

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