M-Cell deficit and reading disability: a preliminary study of the effects of temporal vision-processing therapy


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Background: This study examines the following questions. In moderately disabled readers, will temporal vision-processing therapy procedures that benefit reading comprehension, visual attention, and oculomotor skills ameliorate M-cell processing deficits as measured with coherent motion threshold testing? And will the results show a corresponding improvement in oral reading and verbal skills?

Method: A sample of 16 moderately disabled readers, evaluated in a study completed 6 months earlier, were retested with another form of the Gates-MacGinitie Reading Test. Each participant was additionally tested for coherent motion, oral reading, and word attack skills. During the succeeding 6 months, fifteen 45-minute therapy sessions were administered once a week (as the school schedule permitted). After completing 15 therapy sessions, the initial testing procedures were repeated.

Results: All four variables—namely, Gates-MacGinitie Reading Test, Coherent Motion Threshold Test, Gray Oral Reading Test, and Woodcock-Johnson Word Attack Test—revealed significant improvements after temporal vision therapy. Half of the 16 participants improved 2 or more years in reading comprehension, compared to no significant mean difference following the 6-month “control period” before the onset of therapy.

Conclusions: This research supports the value of rendering temporal vision therapy to children identified as moderately reading disabled (RD). The diagnostic procedures and the dynamic therapeutic techniques discussed in this article have not been previously used for the specific purpose of ameliorating an M-cell deficit. Improved temporal visual-processing skills and enhanced visual motion discrimination appear to have a salutary effect on magnocellular processing and reading comprehension in RD children with M-cell deficits.

Key Words: Children, fMRI, learning, magnocellular, M-cell, reading comprehension, school, temporal visual processing

Research in the neurophysiology of vision during the past decade has enabled optometrists to conceptualize sophisticated clinical procedures for the diagnosis and treatment of temporal visual-processing disorders. Using functional magnetic resonance imaging (fMRI) techniques, investigators have isolated visual functional deficits in specific measurable neurophysiological channels in the brain. These neural pathways—to be discussed subsequently—predominantly involve the magnocellular subsystem that originates in the ganglion cells, the output neurons of the retina, and extend to the extra striate cortex and the frontal eye fields via the posterior parietal cortex. They support the hypothesis that, in some individuals who reveal reduced visual motion sensitivity, reading disability (RD) is associated with a magnocellular (M-cell) deficit. However, rigorous treatment studies with outcomes that are predicated on standardized reading comprehension norms are lacking. Having demonstrated in previous research that middle-grade, moderately disabled readers are less sensitive than normal readers to visual motion stimuli (as measured with coherent motion threshold), the dual purposes of the present study are to review relevant research and to examine the effect of temporal visual-processing therapy on certain neural subsystems attributed to reading disability. We have continued to examine the performance of moderately disabled middle-grade readers. Although they may not reveal the same degree of persistent problems in phonologic awareness as dyslexics, this often-neglected group of middle-grade students frequently manifests temporal visual deficits.

Specifically, the authors question whether improved motion perception that is generated with temporally based vision-processing therapy will:
1. produce significant improvement in coherent motion threshold, a putative measure of magnocellular processing;
2. result in increased reading comprehension, as measured with standardized silent reading tests in a population of children who are less likely to have severe phonologic deficits; and
3. show improvements in oral reading rate and non-word reading, a measure of phonologic awareness.

Literature Review

For more than three decades, vision researchers have recognized the presence in the human brain of two parallel—albeit segregated—visual pathways; namely, magnocellular and parvocellular, each with different neural sensitivities. The magnocellular (M-cell) channel is a motion-detecting subsystem that is responsive to high temporal frequencies, low spatial frequencies, short wavelength of light, and reduced illumination. The rapid saccade fixation pattern, repeated throughout reading, activates this channel, since it is sensitive to stimulus movements across the retina. Its analogue, the parvocellular (P-cell) channel, is involved in processing color information and is more responsive to stationary or slowly moving targets; it has a low sensitivity to contrast and is most sensitive to high spatial frequencies. P-cells are foveally activated during fixations, and extract the details of the text. The two subsystems originate in the retinal ganglion cells and extend, via the lateral geniculate nucleus (LGN), to the visual cortex, striate, and extrastriate areas, where they still remain segregated. The M-cell stream proceeds via the middle temporal (MT and MT+) areas dorsally to the visually responsive posterior parietal (PP) cortex. The MT areas manifest several attention-related response sensitivities, including binocular interactions, perception of real and apparent motion, and eye movements. The lateral intraparietal (LIP) area within the PP cortex serves as a bridge to the frontal eye fields in the prefrontal area of the brain and is associated with saccadic eye movements.

Galaburda’s scholarly review of the presence of left hemisphere microdysgeneses in some post-mortem dyslexic brains that occurred during corticogenesis suggests that the lack of cerebral asymmetry observed frequently in dyslexics may be pathological in origin. Livingstone et al. also
reported a neurobiological basis for an M-cell deficit in reading disability by comparing the LGN of five dyslexic brains to five control brains molecularly, also post-mortem. In the dyslexics' LGNs there was a size reduction of 20% in the M-cells as compared to controls. In contrast, P-cells revealed no significant anatomic differences. Psychophysical vision research, as summarized by Lovegrove, implicated deficits in visual pattern masking, contrast sensitivity as a function of spatial frequency, temporal frequency using critical flicker fusion frequency (CFF), luminance, and wavelength in reading disabled subjects. Facoetti et al., describing the effects of training visual spatial attention in the peripheral visual fields of elementary grade Italian school children, reported significant improvements in their reading abilities; however, they questioned the potential value of the procedures in languages other than Italian.

Eden and Zeffiro obtained further evidence of anatomic and neurophysiological abnormalities in brains of patients with dyslexia using functional magnetic resonance imaging (fMRI) techniques. They concluded that, in individuals with M-cell deficits, vision disorders may be just as much a component of dyslexia as language disorders. Using coherent motion threshold visual stimuli [random dot kinematogram, or RDK], Eden et al. performed additional studies to demonstrate that fMRI testing provides psychophysical and anatomic evidence of an anomaly of the M-cell visual subsystem. The RDK stimuli (see Figure) required functional motion processing in the MT area of normal and dyslexic adult men. In all dyslexics, presentation of moving stimuli failed to produce the same task-related activation in area V5/MT, as observed in controls. In 1998, Demb, Boyton, and Heeger used fMRI analysis to demonstrate a strong correlation ($r = +0.80; p < 0.005$) between variations in MT and variations in reading rate. Brain activity, as measured in the MT area, provides a psychophysical measure that accounts for 64% ($r^2$) of the variations in reading rate.

More specifically, Talcott et al. compared 18 adults with dyslexia and 18 controls on two different tasks of putative visual magnocellular function; namely, CFF for critical flicker fusion frequency and RDK for detection of coherent motion threshold. Dyslexics were significantly less sensitive than controls in each test. They showed increased difficulty in differentiating motion coherence from random dynamic noise as compared to controls. In a subsequent study, Talcott et al. attempted to modify the experimental variables. They concluded that increasing stimulus duration did not improve dyslexics' performance, but increasing dot density did. Apparently, increasing motion energy in the latter experiment improved the dyslexics' signal-to-noise ratio. By testing Grade 6 children, Solan et al. confirmed that coherent motion sensitivity significantly differentiates above- and below-average readers. The studies involving RDK support the hypothesis that, in some individuals, reading disability is correlated with poor global motion processing as measured by coherent motion threshold. They reinforce the position that a neurocognitive link exists in the interrelations of M pathway integrity, perception of visual motion, and reading ability in children and adults.

The research of Eden, Stein, and Wood (1993) reminds us that visual spatial and verbal tasks also significantly correlate with reading ability. The study included copying a complex figure, left-right dot localization, vertical tracking, and eye movement fixations. Among the verbal-phonological skills, significant differences were observed between normal and disabled readers with the Test of Auditory Analysis and Pig Latin Completion Time. The visual tasks were almost as useful in discriminating between good and poor readers as were the phonological tests. Eden et al. (1995) confirmed and expanded their earlier study using a larger sample to determine whether the earlier findings held true. Visual performance tests for fixation stability, vergence ability, and vertical tracking proved to be significantly more difficult for RDs than for non-disabled (ND) 5th graders. A high proportion of the variance in reading ability of both ND and RD children has been shown by combining visual and phonologic scores in a multiple regression analysis. Although RD and ND groups differed significantly in their phonologic and visuo-spatial performances, it would be simplistic to interpret the characteristics as cause and effect. Nevertheless, their study...
Table 1. Mean scores and standard deviations for all dependent measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>T0: 7 months before T1</th>
<th>T1: Pre-therapy</th>
<th>T2: Post-therapy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM Grade Equivalent (GMGE)</td>
<td>4.18 (0.48)</td>
<td>4.48 (0.98)</td>
<td>6.52 (1.41)</td>
</tr>
<tr>
<td>GM Normal Curve Equivalent (GMNCE)</td>
<td>31.25 (3.98)</td>
<td>*30.44 (8.07)</td>
<td>42.94 (8.31)</td>
</tr>
<tr>
<td>GM Percentile Score (GMPer)</td>
<td>19.13 (5.28)</td>
<td>21.25 (10.32)</td>
<td>41.13 (14.95)</td>
</tr>
<tr>
<td>Coherent Motion Threshold Test (Percent)</td>
<td>Not available</td>
<td>6.88 (3.75)</td>
<td>4.98 (2.13)</td>
</tr>
<tr>
<td>Grey Oral Reading test, w.p.m. (GORT)</td>
<td>Not available</td>
<td>131.81 (21.84)</td>
<td>160.00 (30.63)</td>
</tr>
<tr>
<td>Woodcock–Johnson Word Attack Test Scaled Score (WJWAT)</td>
<td>Not available</td>
<td>8.63 (1.71)</td>
<td>11.19 (1.68)</td>
</tr>
</tbody>
</table>

* Note that the decline from T0 to T1 reflects the failure of students to make expected gains for their grade level from 6th to 7th grade.

contradicts the view that visual problems are not associated with reading disability.

The current intervention study involves stimulation of early visual-processing subsystems, especially those with potential M-cell deficits. Based on recent advances in neuroscience and the increased understanding of the development of neural mechanisms for reading, the authors hypothesize that improved early perception and processing make visual information more available for verbal cognition and reading; i.e., visual (orthographic) information processing appears to influence the auditory (phonologic) and conceptual (semantic) representations. A similar phenomenon was present in our earlier research, when it became evident that visual attention was the catalyst that appeared to link perception with cognition.

**Method**

**Participants**

Twenty-seven RD seventh grade students (mean age = 12.4 ± 0.4 years), who had participated in our previous research at a neighborhood middle school, were identified. Twenty volunteered to continue in this study, and 16 completed the program. Since the earlier study was controlled, we considered it unnecessary to repeat the entire process. The school serves a mixed middle-class population consisting of European-American, Asian-American, Hispanic, and African-American children. An informed consent letter that required a parent and the participant to agree to the therapy program as outlined was completed by each family. The research was approved by the college’s institutional review board (IRB) and the Proposal Review Committee of the New York City Department of Education. The investigators completed the CITI human research ethics program.

The mean pre-therapy reading grade equivalent (GE) on the comprehension subtest of the Gates–MacGinitie Reading Test (level 5/6) obtained for the 16 RD students using Grade 7 norms was GE 4.48 ± 0.98 (percentile equivalent: 21.25 ± 10.32),* about 2.7 years below their school grade (see Table 1). Except for three grade 3 readers (whose scores were included in the statistics), initial reading comprehension scores ranged from 0.5 to 1 SD below the mean (16th to 31st percentile). A vision screening for visual acuity at far and near, hyperopia, near point phoria, and binocular fusion identified four children with mild vision disorders. Parents were notified and urged to have their children’s eyes examined. Since the visual deficits were minimal, the students were included in the study.

**Procedures**

Each participant was tested for coherent motion threshold under low photopic luminance conditions. A Dell laptop computer (Model PP021), with the viewing distance of the screen 20 inches (51 cm) away, was placed directly in front and along the midline of the student. The student observed two rectangular patches on the screen, side by side, separated by 5 degrees, each with 150 high luminance white dots presented on a nominal black background (see Figure). At this distance, the rectangular patches were 10 degrees wide and 14 degrees high, and they were displayed on a high-

* Alternate forms, K & L, of the Gates–MacGinitie Reading Comprehension Test, 3rd ed. (1989), were administered before and after the therapy, respectively.
resolution LCD screen for a total presentation time of 2.3 seconds. Once seated, subjects were monitored closely by the tester to prevent any gross bodily movements that would change the visual angle of the stimuli on the subject's retina. In one rectangle, all dots appeared to move randomly in a Brownian motion (random walk), while in the other rectangle a varying percentage of the dots appeared to move horizontally to and fro while the remaining dots moved in a random walk. Each dot had a finite lifetime (225 ms), after which it was replotted randomly at some other position within the stimulus patch, thus eliminating the possibility that the task could be performed by tracking individual dots. Coherent motion threshold percentage was determined by the minimum number of dots that appeared to move together laterally in a single direction on the horizontal axis (corrected for the effect of finite dot lifetime) divided by 150, the total number of dots. Demonstration trials illustrating coherent motion preceded the actual testing. The two conditions, coherent or random motion, alternated between the left and right rectangles at random. After each display period, the student selected the designated key on the left or right side of the keyboard that represented observing coherent motion in the left or right rectangle. A modified 1-up-1-down staircase method of limits procedure was used, in which eight reversals were required for trial termination. Incorrect responses led to an increase in the stimulus value by 3 dB. After the two series of displays—Trial 1 and Trial 2—the testing was concluded, and the results were averaged. A subject's threshold was defined as the geometric mean of the coherence score for the last eight of 10 reversals. The coherence score, expressed as percentage of moving dots, represented the minimum number laterally moving, as compared to randomly moving dots necessary for accurate detection of coherent motion.\(^{13,14}\)

Because the test uses a two-alternative, forced-choice procedure, with stimuli varying unpredictably in each rectangle, guessing was permitted. Individuals with better motion sensitivity would have a lower detection threshold, since they would require a smaller percentage of the dots to be moving to perceive the appropriate motion, while the opposite would be true for the participants with a poorer coherent motion detection threshold. The latter condition suggested a magnocellular deficit.

The mean reading level of the participants was middle grade 4, which suggested that visual processing, rather than solely basic decoding skills, was a fundamental problem. The Woodcock-Johnson Word Attack (non-word) Test and the Gray Oral Reading Test (GOR) were administered to obtain a measure of verbal functioning before and after vision therapy. In the former test, the participant is required to read each word fluently (smoothly); the GOR is a timed test that is validated by answering five simple questions after reading a brief paragraph.

**Therapy**

Fifteen 45-minute vision therapy sessions involved several stimulus-driven and goal-directed voluntary procedures. To realize optimum therapeutic gains, the 16 participants were provided the opportunity to develop improved visual attention\(^{19}\) and cognitive strategies, sometimes referred to as executive functioning.\(^{20}\) The former emphasizes arousal, activation, and vigilance; the latter encourages the individual development of efficient learning tactics. Predominantly, the therapy reinforced attributes that are associated with the magnocellular visual subsystem, such as attention\(^{21,22}\) and sensitivity to moving targets,\(^{11}\) and low and middle spatial frequencies. In efficient reading, the pre-motor model of oculomotor readiness makes the assumption that visual attention shifts to the next target location before a saccade can be executed to that location—i.e., subsequent to completing initial processing of the foveal input, programming of the next saccade begins after visual attention shifts from the fovea to the right parafoveal area.\(^{23,24}\) This aspect of the therapy was comparable to the orienting and focusing spatial procedures reported by Facoetti et al.\(^{9}\) All procedures were administered individually and involved computer-assisted programs. Using a rotating plan, four or five of the six programs were used in each of the fifteen 45-minute sessions. Difficulty levels were increased gradually to maintain the success-oriented nature of the therapy, an approach that seemed to encourage intrinsic motivation.\(^{25}\) Careful achievement records were maintained.

Because rapid on-off and visual motion stimuli are known to drive the M-cell subsystem, most sessions included the Perceptual Accuracy–Visual Efficiency (PAVE) program,\(^*\) which consists of tachistoscopic

\* Related technical information and procedures are available from: Taylor Associates/Communications Associates/Communications, Inc., 200–2 East 2nd Street, Huntington, New York 11746.
Table 2. t-Tests

<table>
<thead>
<tr>
<th>Pair</th>
<th>GMNCE 1</th>
<th>GMNCE 2</th>
<th>Mean differences</th>
<th>SD</th>
<th>t</th>
<th>N</th>
<th>Significance (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>12.50</td>
<td>10.02</td>
<td>4.990</td>
<td>15</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>CMTT 1</td>
<td>CMTT 2</td>
<td>1.90</td>
<td>2.64</td>
<td>-2.887</td>
<td>15</td>
<td>0.011</td>
</tr>
<tr>
<td>3</td>
<td>GORT 1</td>
<td>GORT 2</td>
<td>28.19</td>
<td>30.16</td>
<td>3.7381</td>
<td>15</td>
<td>0.002</td>
</tr>
<tr>
<td>4</td>
<td>WJWA 1</td>
<td>WJWA 2</td>
<td>2.56</td>
<td>1.71</td>
<td>5.989</td>
<td>15</td>
<td>0.001</td>
</tr>
</tbody>
</table>

SD, Standard deviation; GMNCE, Gates-MacGinitie Reading Comprehension Normal Curve Equivalence, Test 1, 2; CMTT, Coherent Motion Threshold, Test 1, 2; GORT, Gray Oral Reading, Test 1, 2 (wpm); and WJWA, Woodcock-Johnson Word Attack, Test 1, 2 (scaled score).

exposure practice and oculomotor efficiency. Perceptual Accuracy therapy comprises temporal processing or rate of perception. It applies to the processing of stimuli that are presented rapidly (e.g., ≤ 100 ms), as when flashed with a tachistoscope. Visual Efficiency is associated with the perception of rate as it pertains to oculomotor skills that require dynamic stimulus detection, an important therapeautic attribute. The participant counts the frequency of appearances of a particular digit or letter while following a left-to-right sequential presentation of three equally placed characters per line on a computer screen, usually starting at 40 lines per minute (lpm) and continuing to 120 lpm. Sixty lpm is equivalent to one line per second (lps), or a fixation duration for each character of about 330 ms. Since the coherent motion threshold testing initially revealed that almost all the participants had an M-cell deficit, an additional program to improve right parafoveal awareness was created to enhance oculomotor readiness.* To improve reading fluency, dynamic visual processing therapy that included content was provided with Guided Reading.† The children were required to read at their independent reading levels as they followed a moving left-to-right horizontal aperture that exposed three words at a time.26 Additional effective therapeutic procedures included:

1. Visual Search, which required the student to rapidly identify and delete stimuli, consisting of 4 or 5 letters or numbers in an array organized into five columns and 15 rows;
2. Visual Scan, in which the participant locates and cancels designated target stimuli (e.g., 25 numbers) "hidden" in a randomized array of distractor stimuli (e.g., 125 letters).*

In each of these goal-directed, timed programs, development of parafoveal and peripheral awareness are encouraged. The programs enhance arousal and alertness, shifting and sustained attention, and figure ground awareness.

To maintain a high level of participation, the need to include a modicum of behavioral modification was apparent. Therefore, the therapists encouraged the development of intrinsic motivation by periodically reminding the participants of their increasing success in performing the various tasks.25

Results

Although the 16 participants were in grade 7.2, initially their mean grade equivalent (GE) reading score was GE 4.48 (SD = ± 0.98). Table 1 presents the original reading scores at T0, 7 months prior to T1. It also compares pre- and

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* Further information may be obtained from: RC Instruments, P.O. Box 6028, Apache Junction, Arkansas 85278.
† Related technical information and procedures are available from: Taylor Associates/Communications Associates/Communications, Inc., 200–2 East 2nd Street, Huntington, New York 11746.
Table 3, A. Gates-MacGinitie Comprehension Test: effects of therapy over all three measurement periods (− 7 mo., pre-, and post-therapy)

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
<td>1565.375</td>
<td>2</td>
<td>782.687</td>
<td>28.273</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Error (Training)</td>
<td>1223.958</td>
<td>30</td>
<td>40.799</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3, B. Pairwise comparisons for testing sessions

<table>
<thead>
<tr>
<th>Time</th>
<th>Mean difference</th>
<th>SE</th>
<th>Significance (p value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>T1</td>
<td>0.813</td>
<td>1.856</td>
</tr>
<tr>
<td>T2</td>
<td>11.688*</td>
<td>2.362</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>T1</td>
<td>T0</td>
<td>-11.688</td>
<td>2.362</td>
</tr>
<tr>
<td>T2</td>
<td>-12.500</td>
<td>2.505</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>T2</td>
<td>T0</td>
<td>11.688*</td>
<td>2.362</td>
</tr>
<tr>
<td>T1</td>
<td>12.500*</td>
<td>2.505</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Based on estimated marginal means (GMNCE).

* The mean difference is significant at the 0.05 level.

SE, Standard error; T0, 7 months before testing; T1, pre-therapy; and T2, post-therapy.

post-therapy (T1 and T2) mean scores of the dependent variables before and after 15 sessions. The results of t-tests (two-tailed) presented in Table 2 show significant improvements between the means in the four diagnostic tests:

[GMNCE] Gates-MacGinitie Reading Comprehension Scores \( t = 4.990, p = 0.001 \);*
[CMTT] Coherent Motion Threshold Test \( t = -2.887, p = 0.011 \);
[GORT] Gray Oral Reading Test \( t = 3.738, p = 0.002 \); and
[WJWAT] Woodcock-Johnson Word Attack Test \( t = 5.989, p = 0.001 \). Although they did not attain grade level, the three grade 3 readers improved an average of 3 years.

To assess the changes in reading comprehension and coherent motion before and after 6 months of therapy, it was necessary to establish post-therapy minimum improvement criteria. For GMNCE, we used an increment equal to or greater than +1.5 years \( (\geq 1.3 \text{ SEM}) \). Nine of the 16 students met these standards for both variables. In addition, one satisfied GMG, but not CMTT, and two satisfied CMTT, but not GMGE.

One might question: Would the change in reading comprehension have taken place without vision therapy? Since each student’s reading comprehension had been tested 7 months earlier \( (T0) \), they served as a control group.15 A repeated measures analysis of variance (ANOVA) of the GMNCE was computed to determine whether the participants improved in reading over time in the absence of therapy \( (T0-T1) \) compared to the within-subjects reading growth after therapy \( (T1-T2) \). Overall, the ANOVA yielded significant change across T0-T2 \( (F = 19.184, p < 0.001; \text{see Table 3, A}) \). Multiple comparisons \( \text{see Table 3, B} \) indicate that improvement in reading comprehension during the pre-therapy period \( (T0-T1) \) was not significant \( (p = 0.668) \); however, after 15 vision therapy sessions \( (T1-T2) \) the participants’ mean NCE scores showed significant improvements, \( (p < 0.001) \). In percentile terms, they progressed from the 21st to the 41st percentile \( \text{see Table 1} \).

Discussion
The precise nature of the complex visual and verbal linguistic processing skills associated with
reading disability has remained a source of controversy for more than one hundred years after Hinshelwood first described Word Blindness. Abundant research has shown that deficits in auditory and temporal visual skills contribute to reading difficulties. Eden and Moats propose that the exact mechanisms by which the brain recovers phonemes and associates them with visually presented orthography remain elusive. Despite gains in understanding the neurobiological concomitants of reading fluency, experts do not completely agree on the most effective intervention in either the verbal or visual domain. For example, two contrasting theories—a metalinguistic (language-based) deficit hypothesis versus a temporal processing deficit in the auditory system—represent divergent research approaches. Similar uncertainties exist in dealing with the visual domain: Is the treatment of RDs more effective when the therapeutic regimen stresses improving the quality and range of binocular fusional reserves and accommodative facility, so that the affected individuals may visually sustain effort more comfortably and attend for extended periods of time? Or should vision therapy stress dynamic visual stimuli to ameliorate a deficit in the magnocellular system as determined by fMRI and/or coherent motion analysis? Although abundant evidence is extant to support the presence of vision deficits in individuals with RD, there has been a paucity of research directed toward the value of specific vision therapy procedures in the treatment of M-cell deficits.

In a previous study, with a similar population of middle-grade RDs, vision-processing therapy resulted in significant improvements in reading comprehension and eye movements. However, the participants were not measured for coherent motion sensitivity before or after vision therapy. Furthermore, the precise role of increased visio-temporal motion sensitivity was not quantified. To correct the latter, a subsequent group of grade 6 RDs (experimental) was tested for reading comprehension and attention before and after receiving therapy with carefully selected non-verbal dynamic stimuli, as described in the 'Therapy section'. A control group received no therapy and showed no improvement in reading comprehension. Only the experimental sample showed significant improvements in reading comprehension.

Our recent research verified that coherent motion threshold measurements for M-cell deficit differ significantly for good and below average readers in grade 6 students. Of the 20 below-average readers who volunteered to participate in the present study—now in grade 7 six months later—16 completed the program and served as a control group. The relatively small sample size has caused certain statistical limitations for this preliminary study; nevertheless, the outcome has been impressive: after vision therapy, 10 of the 16 improved 1.5 years or more in reading comprehension (2 SEM). Eleven of the 16 recognized lateral motion at a 15% lower coherent motion threshold, which indicated increased M-cell sensitivity (2 SEM). Both functions are malleable; nevertheless, the results should not be interpreted to imply that a magnocellular deficit is the sole cause of reading disabilities.

The current coherent motion research differs from previous studies in several ways: first, many of the earlier studies involved only adults whose attention, the authors said, was more reliable than grade 7 RD students; second, their participants were described as "dyslexic," which suggested that their reading levels were lower than the moderately disabled children in the present study. Furthermore, the earlier research did not consider the effect of vision therapy on a magnocellular deficit and reading disability. Moreover, the increased sensitivity to coherent motion threshold after therapy suggests a potential magnocellular pathway's role in efficient reading eye movements. Neither eye movements nor attention have been measured in the current research; however, their inter-relationship to coherent motion and M-cell deficit before and after therapy will be examined in a subsequent study.

Although the temporal therapy stressed visual stimuli, positive changes also were measured across sensory modalities; namely, phonologic and orthographic. Not only were the mean improvements in reading comprehension and coherent motion threshold significant, but the participants also realized significant improvements in the Gray Oral Reading and the Woodcock-Johnson Word Attack Skills Tests. Our results agree with the proposal of Witton et al. that good visual temporal processing skills appear to be necessary for the accurate encoding of letter position that is required for accurate reading. Nevertheless, it should be recognized that this research is a pre-

liminary study with a relatively limited control group and sample size.

It would be naive to suggest that auditory and visual-processing deficits that exist in some RD children are mutually exclusive. To concentrate remediation solely in either modality would be counterproductive, since auditory-visual integration is basic in learning to read. For example, in the current research, after 15 sessions (12 hours) of temporal vision therapy, mean reading comprehension for the sixteen 12-year-old students improved from the 21st to the 41st percentile on the Gates–MacGinitie Reading Tests. In addition, significant improvement was measured on two verbal tests, the GOR Test and the W–J Word Attack Test. On the other hand, Temple et al., using a very different selection criterion, provided 20 children (8- to 12-years-old) with a remediation program that focused on auditory processing and oral language training, but used tests that required visual processing to assess the outcome. The children attended sessions 100 minutes per day, 5 days per week, for an average of 27.9 days (47 hours). The average pre-training scores on three subtests of the W–J Reading Mastery Test (Word ID, Word Attack, Passage Comp) was 12th percentile, as compared to 25th percentile after training. Their study complements the present research. Together, they lend support to the value of temporal vision therapy and auditory processing/oral language training, plus the potential for verbal-visual reciprocity in the treatment of RD children. An examination of the results of fMRI testing in dyslexics by Temple et al. and Eden et al. confirmed that the brain is not entirely compartmentalized, and collateral effects are the rule. For example, Temple et al. reported that auditory processing-verbal language therapy revealed increased activity in the areas associated with attention and visual processing. Eden et al., studying abnormal processing of visual motion in dyslexia, observed visual perceptual processing deficits that implicated the temporal characteristics of the M-cell system. This deficit may manifest itself as disorders of phonological awareness, rapid naming, as well as rapid visual processing. The moderately disabled readers in this research initially did not reveal phonologic disorders similar to those sometimes observed in “true dyslexics”; therefore, it is reasonable to assume that the temporal visual-processing therapy had a salutary effect on their reading performance.

Stein and Walsh were correct in proposing "...reading disabilities emerge not from a single visual relay, but from abnormalities of the magnocellular component of the visual system, which is specialized for processing fast temporal information. The M-stream culminates in the posterior parietal cortex, which plays an important role in guiding visual attention. The evidence is consistent with an increasingly sophisticated account of dyslexia that does not single out either phonological, or visual, or motor deficits. Rather, temporal processing in all three systems seems to be impaired. Dyslexics may be unable to process fast incoming sensory information adequately in any domain."

Looking Ahead

As is often the case, this preliminary study suggests additional avenues of inquiry into the effects of vision therapy on reading comprehension. For example, improving the quality of binocular fusion, accommodative facility, and hand-eye coordination should be compared with temporal (dynamic) vision-processing therapy using a crossover study. Are they complementary? And, if so, which should be administered first to be most effective? The efficacy of the procedures should be explored when applied to middle-grade students with more-serious reading disabilities. Moreover, answering the question "Is there a common linkage between reading comprehension, visual attention, and magnocellular processing?" would provide us with a measure of the sensitivity of visual attention and coherent motion threshold as they relate to reading comprehension.

Available research supports the notion that eye movements in reading, measured objectively with the Visagraph, can be improved significantly with appropriate therapy. Nevertheless, it would be valuable to learn more about the relationship of reading eye movements to magnocellular processing, as measured with coherent motion. For example, are inefficient reading eye movement patterns a clinical sign of a more-generalized M-cell deficit? Certainly, the role of visual spatial attention as a concomitant of eye movements warrants further examination. Moreover, there is evidence that visual attention is a magnocellular function. Will improvement in visual attention, as measured with Cognitive Assessment System before and after temporal vision therapy, result in an increased coherent motion threshold sensitivity?
Functional neuro-imaging studies using fMRI are currently in progress to investigate magnocellular deficits in dyslexia. This technique provides an opportunity to identify the regional specialization and spatial congruence of the cortical areas engaged in visual, auditory, and linguistic processing. Studying the cross-modal effects that temporal vision therapy may have on the magnocellular visual system and the auditory processing system could provide significant information concerning neural plasticity in these cortical areas in middle-grade RD children.

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