

# Article

## Training Direction-Discrimination Sensitivity Remediates a Wide Spectrum of Reading Skills

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### ABSTRACT

**Background:** This study investigated whether timing deficits in the motion pathways represent a core deficit in inefficient readers who are dyslexic.

**Methods:** Inefficient and efficient readers in grades 2 and 3 in four public elementary schools were studied. Component literacy skills were measured before and after training. In the training task of interest, participants judged the direction of motion (left vs. right) of a vertically oriented sinusoidal grating, surrounded by one of five different background frequencies. The threshold contrast for direction discrimination was measured.

**Results:** Direction discrimination improved the most for inefficient readers following training. Moreover, following training the time to complete the task decreased significantly, showing that the timing of direction discrimination improves, as does the gain. For inefficient readers, training on direction discrimination resulted in significant improvements in reading efficiency and fluency. Inefficient readers in control conditions showed minimal improvement.

**Conclusions:** Significant improvements in reading performance were found following training on direction discrimination. This study provides evidence that timing deficits in inefficient readers represent a core deficit.

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*In the interest of full disclosure, it should be noted that Dr. Lawton has a significant financial interest in many of the topics/therapies discussed in this article.*

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### KEY WORDS

contrast sensitivity, direction discrimination, dyslexia, inefficient readers, magnocellular deficit, reading remediation, perceptual learning, cortical plasticity.

### INTRODUCTION

Dyslexia can be defined to be partial alexia in which letters but not words may be read, or in which words may not be decoded (word recognition) or encoded (word recall for proper spelling) according to normal levels.<sup>1</sup> Dyslexia is a multifaceted learning disability that encompasses both pronunciation-based and visual processing-based issues. Until recently, the core deficit underlying reading disabilities was assumed to be a phonological processing deficit.<sup>2-5</sup> New research extends this view to incorporate an additional second core deficit in timing (measured using rapid automatized naming).<sup>6-8</sup> The speed of naming digits, letters, and objects of dyslexic readers, highly correlated with word reading speed, contributes uniquely to reading ability in grades 2-4,<sup>9,10</sup> and is a good test to discriminate between efficient and inefficient readers.<sup>6,11,12</sup> Slow reading speeds are a hallmark of dyslexia. In fact the timing deficits in naming speed are better predictors of reading problems than found using deficits in phonological processing.<sup>6</sup>

Children with dyslexia are reported to have some combination of spatial<sup>13-16</sup> and/or temporal<sup>17-20</sup> sequencing deficits, which may cause the letters in the words and the words on the page to appear distorted, displaced, or crowded together.<sup>21</sup> These spatial and temporal sequencing difficulties are believed to result from neural timing deficits since they only occur with rapidly presented images. Dyslexic readers also show motion discrimination deficits, including an impaired ability to discriminate both the direction<sup>22-28</sup> and the

velocity<sup>29,30</sup> of visual patterns. Timing deficits manifest themselves as an impaired ability to discriminate the direction of motion (a core deficiency in inefficient readers) and may result from problems in the cortical direction-selectivity network.<sup>22-24, 46, 50</sup>

Several results suggest that reading fluency can be improved by training that focuses on the magnocellular pathway. In particular, Solan et al<sup>31</sup> have demonstrated that a training regimen (45 minutes per week, over 12 weeks) including a battery of tasks emphasizing dynamic visual processing improves reading fluency in moderately impaired readers. The current study differs from that of Solan et al<sup>31</sup> in using a briefer training regimen (20 minutes per week, over 15 weeks) comprising a more focused set of tasks (exclusively left-right motion discrimination using low contrast sinusoidal gratings). Indeed, previous studies suggest that this very simple regimen is highly effective at improving reading speed for continuous text in inefficient readers.<sup>22-24</sup> This finding is remarkable, since perceptual learning rarely generalizes to a new task.<sup>32-34</sup>

It is notable that when dyslexic readers were trained on direction discrimination using elementary motion discrimination tasks, a wide spectrum of reading skills improved significantly<sup>23,24</sup> including fluency, reading speed, comprehension, word identification and spelling. This improvement for inefficient readers was significantly more than found for matched-sample control groups who practiced a word discrimination game or only had the school's regular reading program.<sup>23,24</sup> Moreover, these studies also found that inefficient readers in second grade who were trained on left-right movement discrimination improved in reading fluency significantly more than did efficient readers.

This clinical validation study extends these results by investigating whether systematically increasing the complexity of the background pattern which activates a wider range of channels tuned to different spatial frequencies, enables even larger improvements in reading fluency following training on direction-discrimination. Moreover, this study investigates if increasing the frequency of training increases the effect.

## Methods

Perception Dynamics Institute (PDI) conducted controlled clinical studies during the school year 2003-2004. This study involved second and third grade students recruited from 4 public elementary schools in Santa Monica and Los Angeles, CA following approval by school administrators and individual teachers who decided to have their entire class participate.

Standardized tests of reading skills were administered to every student in the study. These tests were: 1. A

computer-based reading speed assessment (see below), 2. Decoding-Encoding Screener for Dyslexia (DES-D), 3. Wide Range Achievement Test (WRAT-3) reading (word identification) subtest, 4. WRAT-3 spelling subtest, and 5. Gray Silent Reading Test (GSRT).

The intervention of interest (Moving To Read (MTR) therapy described below) is hypothesized to improve reading fluency. This dimension of reading skill is most directly measured by the computer-based reading speed assessment. In this test, continuous, non-repeating lines of text from the *Frog and Toad* series by Arnold Lobel for second grade students, and *Stuart Little* by E.B. White for third grade students (interesting, easy-to-read stories) were presented on the display six words at a time, so that (1) there was no crowding from adjacent words above or below the line being read, and (2) at least two saccades were required to read each line of text. The text was rendered using large (0.5 cm wide by 0.5 to 0.75 cm high) white *sans-serif* letters. The six words of white text were centered in a black window, 1.5 cm high by 14.5 cm wide. The black window was centered in a gray display window that was set to the mean luminance of 50 cd/m.<sup>2</sup> The child could read the six words of text either as they were being presented or when the presentation was finished. Therefore, the reading rate was not limited by the child's rate of speaking. The experimenter chose a rate of text presentation that was continuous and comfortable for the child. Initially the speed of presentation was increased from 40 words/min until five out of six words were not read correctly. At the first incorrect response, a two alternative forced-choice (2AFC) double staircase procedure was implemented, decreasing the speed by one step (12%) each time the text was not correctly identified, and increasing the speed one step only when the child correctly read three successive lines of text. During this task the child was corrected after pronouncing a word incorrectly, and was asked to repeat only the words missed in the six words of text. The same phrase was only shown two times in a row, so that difficult phrases were not a stumbling block in this task. The mean reading-speed threshold was computed from two measurements, each being the mean of the last three out of six reversals in reading speed. This task took about 10 minutes to complete. The relative improvement in reading speed was determined by dividing the final reading speed by the initial reading speed.

## Subject selection and training

The author trained and worked with computer laboratory teachers, individual classroom teachers, and their teaching assistants who were responsible for administering the MovingToRead (MTR) therapy in either the computer lab or in the classroom. The

administration of the standardized tests in the beginning and end of this study was overseen by the author with the assistance of teachers and teacher aids in over 16 classrooms distributed across the four schools. Group testing in each classroom was used to administer the GSRT and the Spelling subtest of the WRAT-3. Individual testing was used to administer the WRAT-3 word identification task, the DES-D, a newer version of The Dyslexia Screener.<sup>35</sup> the DES-D, a newer version of The Dyslexia Screener. Children were never told the correctness of their response, but were given positive feedback to encourage them to be relaxed and perform at their abilities. Eighty percent of computer-based reading rates were measured by the teacher's assistant.

Only children in mainstream classrooms who had normal or above normal intelligence were included in this study. If a teacher decided to participate, then the entire class was included in the study. Children assigned to control groups were done so either randomly, or in a counterbalanced fashion. Children from classrooms with malfunctioning computers were put into the control group that served as the no-game condition, only receiving the school's regular reading program. The 16 classrooms were trained on MTR therapy at different frequencies, enabling a systematic investigation of the effect of increasing the frequency of training on the amounts of improvements found for different reading skills. Classrooms were trained on MTR therapy at least once a week, when previously students were trained on MTR therapy twice a week.<sup>23,24</sup> Standardized literacy tests were administered after a three-month interval for every classroom in this study except for two classrooms of second graders (who were trained on direction discrimination more than 20 times over a 6-month time interval, instead of a three-month interval).

Based on the DES-D, 41 inefficient readers and 65 efficient readers in grades 2 to 3 from four public elementary schools were included in this study, most being between 7-9 years old. There were 24 inefficient readers and 35 efficient readers in second grade, distributed across three schools and 17 inefficient readers and 30 efficient readers in third grade, distributed across four schools. Only students who had no known visual, neurological, or emotional deficits were included. One classroom of children in this study in third grade participated in the previous controlled validation study<sup>23,24</sup> when they were in second grade. Studying this classroom enabled determining whether the improvements measured in second grade carried over to third grade.

The subject selection procedure resulted in an ethnic distribution consisting of an approximately equal number of male and female students, having the

following ethnic and racial distribution: 30% Hispanic, 51% Caucasian, 11% Asian, and 8% African American students. The 41 inefficient readers were distributed across the three groups as follows: MTR therapy: 32, word game: 13, no game: 12. The large number practicing MTR therapy resulted from 18 subjects serving as their own control, in either the word game or no game conditions. The 65 efficient readers were distributed across the three groups as follows: MTR therapy: 49, word game: 14, no game: 19, where 21 subjects served as their own control.

Administering the battery of standardized tests was not influenced by the group to which the child was assigned. This was a masked study. The reading speed and contrast threshold data, having date and time stamps in several files in different folders, were collected automatically by computer programs, so that once data were collected by the computer, there could be no influence on the results.

Students received instructions that were comprehensive and standardized by watching QuickTime movies (4 min). When needed students were provided with one-on-one instruction.

### Procedures

This study compared practicing left-right movement discrimination (MTR therapy) with practicing a 10-minute word discrimination game with only doing the school's reading program. The word discrimination game was a control therapy with high potential for improving reading skills. There was no biasing towards one computer game versus the other. The background complexity was increased in this study for the first time, by using multi-frequency backgrounds, in addition to sinewave gratings to increase the student's motivation to continue playing, and to activate a wider range of visual channels tuned to different spatial frequencies. MTR therapy was used with different frequencies, since the teachers in the classroom ran the study in each classroom. Some teachers occasionally used MTR therapy twice a week while most used it once a week.

The computer game was played in the classroom or in the computer lab. There was one reading assistant to supervise the computer games. Both iMac computers and PC-based computers were used. The child sat 57 cm. from the screen so that the spatial frequency was determined for a fixed viewing distance. The contrast and brightness of each computer screen was calibrated using a Pritchard 1980A photometer.

The intervention therapies were usually administered before directed reading, enabling each child to have plenty of opportunity to practice reading during the school day. Only classrooms where children practiced



reading at least 60 minutes each day were included in this study. The data were analyzed using either one-factor Analysis of Variance (ANOVA) or *t*-tests, when only two groups are compared, to determine whether the differences between treatment and control groups were significant.

### Tasks

The standardized tests were chosen after consulting with leading educational therapists and dyslexia experts to be rapid to administer and having high validity to characterize a student's abilities for learning different aspects of reading. These tests included the DES-D to test phonological and orthographical skills, and sight-word reading grade-level; WRAT-3 to test reading (word identification) and spelling grade level; GSRT to test reading comprehension grade level; and computer-based reading speeds to assess reading fluency. The standardized tests were administered as described previously.

Dyslexia can be expressed as inefficient word recognition and orthographic skills when spelling phonetically irregular words, and/or as poor phonological skills (how parts of a word sound) when decoding and encoding unfamiliar words.<sup>36</sup> Boder<sup>37</sup> introduced the concept of three categories of dyslexia: 1) dyseidetic (trouble with sight-word recognition and spelling phonetically irregular words such as 'laugh' or 'should'), 2) dysphonetic (trouble sounding out words by word attack), and 3) mixed type (both dysphonetic and dyseidetic). The DES-D was based on Boder's<sup>37</sup> differentiation of dyslexic children into three subtypes: dyseidetic (sight word recognition and spelling problems), dysphonetic (problems decoding phonetically), and mixed (both eidetic and phonetic problems) that can be used for rapid diagnosis of the type and severity of dyslexia.

The DES-D was used to classify each student as an inefficient or efficient reader using categories that provide a measure of both the type and severity of the dyslexia. The reading grade level and the number of words spelled correctly either eidetically or phonologically were used to determine the child's classification. The classification was as follows: above normal, normal, borderline normal, mildly below normal, moderately below normal, and markedly below normal, in terms of either decoding (pronunciation) and/or encoding (spelling).

The Dyslexia Screener (TDS),<sup>35</sup> an alternate form of the DES-D, was validated using the Woodcock-Johnson standardized reading tests.<sup>38</sup> The DES-D and the Dyslexia Determination Test (DDT),<sup>36</sup> being a longer version of the DES-D, are the only tests available that

provide a clinically reliable, differential diagnosis for dyslexia. Furthermore, the DES-D reading grade level is based on a strict, timed, sight-word recognition challenge, as opposed to the WRAT-3 which does not. Note that single word sight-recognition is not necessarily equal to the overall reading grade level of individuals, but tends to be for dyslexic individuals. This is likely because poor word recognition is the stumbling block in reading fluency.

The raw score on each reading skills test corresponded to a standardized equivalent grade level, where a grade level of 1 is composed of 6-year-old students, a grade level of 2 for 7-year-old students, and so forth. The equivalent grade level was used to plot the initial and final reading scores and measure the amount of improvement on each of the psychometric tests of literacy. An equivalent grade level was plotted since this is the most relevant information for teachers, school administrators, and parents who take their children to developmental optometrists for vision therapy. The relative improvement in reading skills was determined by comparing the difference between final and initial equivalent grade levels, and/or between the initial and final reading speeds.

### MTR Therapy: Left-right movement discrimination

MTR therapy<sup>22</sup> uses displays (see Figure 1) comprising a stationary, central, "fish-like" window surrounded by a stationary, vertically oriented sinewave grating of spatial frequency  $\omega_{\text{test}}$ . The fish-like window contains a vertical test sinusoid of spatial frequency  $\omega$ . A given trial comprises three frames, each lasting 150 ms. The phase of the test grating on frame 1 is  $\pm 45^\circ$  chosen randomly. On each of frames 2 and 3, the test grating shifts  $90^\circ$  in a fixed direction (either rightward or leftward), and the task of the trainee is to indicate the direction of movement using the right or left arrow key. A brief tone is presented after incorrect responses. At the start of a session, both the test and background gratings are set to 5% contrast. Each time the child correctly identifies the direction the fish stripes move the contrast of the test grating is lowered until the child makes an incorrect response. The step size varies from 0.3% down to a step size of 0.1% at 0% contrast. The low contrasts were obtained by special modifications to the color table varying only one color gun at a time. Following the first incorrect response, a double-staircase procedure<sup>39</sup> was used to estimate the direction discrimination contrast thresholds. Each error increased test grating contrast by one step. The staircase terminated after six reversals and the mean of the last three was taken to estimate contrast threshold *T*. Contrast sensitivity is defined to be  $1/T$ . Three successive correct responses reduce test grating

contrast by one step. This staircase procedure estimates the contrast needed for 79% correct responses.

In this study three consecutive 150 msec time intervals were used to present leftward or rightward movement to ensure that a long duration dynamic stimulus was used and to ensure this task was easy for inefficient readers. Even though apparent motion was used, the motion always appeared smooth because of the fast speeds. Since the sinewave grating moved 90 deg, which is a quarter of a cycle of the spatial periodicity of the center test pattern (one-half a stripe width), in 150 msec, the speed of the test pattern had a constant temporal frequency of 1.7 cycles per second. In other words, one dark and one light stripe traveled almost two times across the fish body in one second. A constant temporal frequency causes the speed to appear faster for low spatial frequencies which subtend a wider spatial extent.

In a given staircase run, the center spatial frequency,  $\omega_{\text{test}}$  is either 0.25, 0.5, 1, or 2 cyc/deg. The surround grating spatial frequency,  $\omega_{\text{background}}$  is either equal to the test frequency or 1 or 2 octaves higher or lower than the test frequency.

A full training cycle of the left-right movement discrimination task requires 20 threshold determinations (i.e. one for each of the four test spatial frequencies paired with each of the five background spatial frequencies).

In addition to the sinewave backgrounds, multi-frequency backgrounds consisting of three spatial frequency components that were bootstrapped to the original sinewave background were used. Bootstrapping was done by setting the fundamental frequency of the background to that of the original sinewave background grating and adding higher spatial frequencies having a difference equal to the test frequency. These frequency combinations were found to facilitate direction discrimination in normal observers.<sup>40,41</sup> Initially both the test and background frequencies were set to 5% contrast to ensure they were presented well above contrast threshold, yet low enough in contrast so that direction-selectivity was optimized.<sup>41,42</sup>

The stimuli used for training on left-right movement discrimination (see Figure 1) were previously found to be optimal for measuring sensitivity of directionally-selective motion pathways.<sup>39-41</sup> The procedure for determining optimal activation of direction-selective motion pathways was as follows: 1) Sinewave gratings (activating both low and high levels in the motion pathways), instead of random dots that active only high levels in the motion pathways were used.<sup>43</sup> Perceptual learning was over 10-fold faster when discriminating the

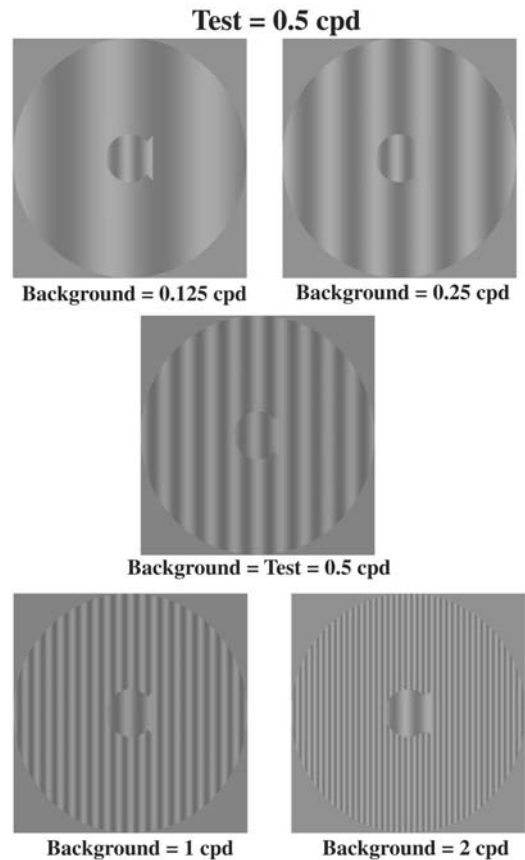


Figure 1. Sample patterns for test frequency = 0.5 cyc/deg (cpd) on different backgrounds.

direction of sinewave gratings<sup>32</sup> than for random dot patterns.<sup>33</sup> 2) The test sinewave grating moved 90 degrees (deg) between the first and second pattern interval, since this is the optimal phase difference for direction discrimination.<sup>39</sup> 3) A range of test frequencies (0.25, 0.5, 1, and 2 cyc/deg) were used to span the spatial frequencies that predominantly activate motion pathways.<sup>42,44,45</sup> 4) A 4-octave range of clearly visible background spatial frequencies, set to 5% contrast, centered around the test spatial frequency was used to map out each channel's spatial frequency tuning function. These background frequencies were an octave apart, since neurons in the direction-selectivity network are tuned to approximately one octave,<sup>44,46</sup> and perceptual learning of direction discrimination does not transfer to spatial frequencies differing by more than one octave.<sup>32</sup> 5) Initially, both the test and background sinewave gratings were presented at 5% contrast, so that these patterns would be in the center of the working range of the magnocellular neurons.<sup>42</sup> 6) The Contrast Sensitivity Function (CSF, the inverse of the contrast threshold function) was used to evaluate a child's direction discrimination ability, since the CSF is most directly related to the output response of a directionally-

selective motion cell.<sup>47</sup> 7) To prevent saccadic eye movements from being involved, left-right movement was presented by having the test sinewave grating move left or right (determined randomly) in 150 msec pattern intervals, since saccadic programming takes around 150 msec.<sup>48</sup> This design also prevented express saccades<sup>49</sup> from contributing to direction discrimination.

Each session (one motion game, taking between 5-10 minutes) consisted of 10 contrast thresholds, involving two test frequencies (in the center of the display) and five background spatial frequencies, ranging in octave intervals from -2 to +2 octaves in spatial frequency from the test frequency (see Figure 1). The test was conducted, for each of two test spatial frequencies, 0.5 and 1 cyc/deg one day, and 2 and 0.25 cyc/deg the second day during the 15 weeks of this study. This order for presenting the test frequencies was chosen to gradually increase the difficulty of the task.<sup>22</sup> Each threshold required 20-30 trials to complete. A score was given to make the intervention therapy more game-like. The lower the contrast threshold, the higher the score.

Two Contrast Sensitivity Functions (CSF) were computed to evaluate the effectiveness of training direction-selectivity. The initial direction discrimination CSF was determined by the contrast sensitivity after completing the first replication. The final CSF was the maximum contrast sensitivity to discriminate the direction of movement for each test-background pattern combination. The CSF data, stored in individual and summary files, were collected automatically by the computer, which also recorded the level of pattern complexity and the time used to complete each set of five patterns (one-half a session).

### **Word discrimination game**

Two classes of second graders and one class of third graders, including both inefficient and efficient readers, practiced a word discrimination game (control group) once a week with each session lasting around ten minutes. There were three different word games, each played on a separate day. The instructions for each word game appeared in writing at the beginning of the game. The first game was the animal game, in which the student pushed the right arrow key if the word was an animal name (bird) and the left arrow key otherwise. The second game was the name game, in which the student pressed the right arrow key if the word was a person's name and the left arrow key otherwise. All words were in lower case letters. The third game was the nonsense game, in which the student pressed the right arrow if the word was a nonsense word, and the left arrow key otherwise. The child received a score of 5 points for correctly pushing the right arrow key, 2 points for correctly pushing the left

arrow key, and lost a point for pushing the wrong key. The word was presented in the middle of the screen until the child pushed either the left or right arrow key. The word then disappeared and a '+' or '-' appeared above the word, and the score was displayed in the upper right corner of the window. The faster the child responded correctly, the faster the words were presented and the higher was their score. This test was timed for 10 minutes and quit automatically when the time was up. The word discrimination game required slightly more attention, since the word had to be detected and its category analyzed, than did left-right movement discrimination. The word discrimination game was played either at the beginning of the study for one third grade classroom, or in the middle of the study for two second grade classrooms.

### **Results**

The DES-D classified 17 inefficient readers as having borderline dyslexia, 14 having mild dyslexia, seven having moderate dyslexia, and three were markedly below normal. Even though the majority of inefficient readers in this study were classified with borderline or mild dyslexia, all of them struggled with reading. Based on the DES-D, there were 31 children who were classified as dysphonetic, one child classified as dyseidetic, and nine children who were both dysphonetic and dyseidetic, or mixed. The children who were mixed inefficient readers were more severe in their reading deficits and ended up practicing MTR therapy more often. They also showed larger improvements in reading skills than the other second graders, as reported below. At the beginning of this study, no significant differences were found between the three groups (MTR therapy, word game, no computer game) of inefficient readers, nor between the three groups of efficient readers on any of the tests of reading skills when analyzed using a 1-factor ANOVA.

Slow reading speeds are a hallmark of dyslexia. Before training, the group of inefficient readers, having a mean reading speed of  $150 \pm 10$  words/min in second grade, and  $159 \pm 12$  words/min in third grade, read significantly more slowly than the average efficient reader having a mean reading speed of  $319 \pm 24$  words/min in second grade, and  $333 \pm 15$  words/min in third grade. These differences were highly significant,  $p < 0.001$ . The initial reading speeds of inefficient and efficient readers in second grade are shown in Figure 2a and in third grade are shown in Figure 2b. The initial reading speeds are grouped by the number of times MTR therapy was used to train direction discrimination. The number of students in each group is listed in the legend of Figure 2. Since each group was trained different amounts



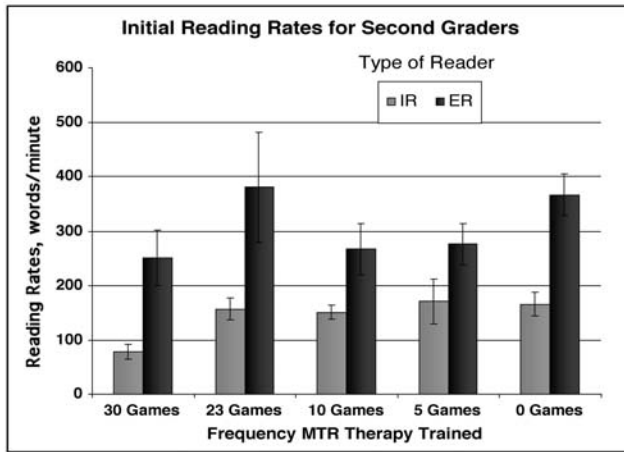


Figure 2a. Initial Reading Rates for Inefficient Readers (IR) and Efficient Readers (ER) in Second Grade in each group that was trained on MTR therapy for different frequencies. The number of students in each group are as follows: 30 Games: 3 IR, 5 ER; 23 Games: 6 IR, 6 ER, 10 Games: 9 IR, 9 ER; 5 Games: 3 IR, 7 ER, 0 Games: 7 IR, 16 ER for a total of 24 IR and 35 ER in second grade. The greater number of children when summed across groups is due to 4 IR and 8 ER being in both the no game group for 3 months before being trained using MTR therapy for 3 months.

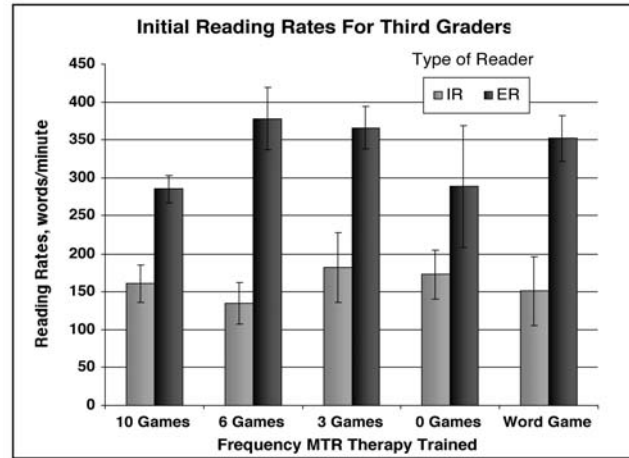


Figure 2b. Initial Reading Rates for Inefficient Readers (IR) and Efficient Readers (ER) in Third Grade in each group that was trained on MTR therapy for different frequencies. The number of students in each group are as follows: 10 Games: 5 IR, 11 ER; 6 Games: 5 IR, 5 ER, 3 Games: 2 IR, 11 ER, 0 Games: 5 IR, 3 ER, Word Game: 2 IR, 4 ER, for a total of 17 IR and 30 ER in third grade. Children who played the Word Game initially for one month, were also trained using MTR therapy for 3 times the subsequent month.

but had approximately the same reading skill, the groups were combined in Figure 3. The initial reading skills are shown for second graders in Figure 3a, and for third graders in Figure 3b. Before training, although both efficient and inefficient readers scored at or above grade level on tests of sight-word recognition and spelling, efficient readers scored at least one grade level, on average, above the average inefficient reader. These differences between inefficient and efficient readers, shown in Figure 3, were highly significant,  $p < 0.001$ , for all reading skills, including reading grade level (word identification), spelling, comprehension, and reading speed.

#### Direction discrimination sensitivity

Figures 4a-c show how movement direction sensitivity improved with training for both efficient and inefficient readers. The more training children had on direction discrimination, the more their direction discrimination CSF increased. This increase was significant for both inefficient readers,  $p < 0.001$ , and for efficient readers,  $p < 0.01$ . This improvement in their direction discrimination CSF was highly significant (see Table 1) even when training consisted of 10 motion games. This improvement was nine to 14 fold for inefficient readers and five to seven fold for efficient readers. Therefore, increasing the complexity of the background was an effective training stimulus.

When the frequency of training was 20-30 times (Figure 4a) the maximum contrast sensitivity was much higher than when the frequency of training was 10 times (Figure 4b for second graders and Figure 4c for third graders). Black lines show results for efficient readers,

and gray lines show results for inefficient readers. Only the CSF for test frequencies of 1 cyc/deg were plotted. As noted previously,<sup>22,24</sup> this was the most sensitive and representative CSF.

The inefficient readers in third grade started with a higher contrast sensitivity than those in second grade (Figures 4b and 4c) suggesting that the more immature the motion pathways, the greater the improvement in the CSF following training. These results demonstrate that inefficient readers have immature directionally-selective pathways that develop rapidly following 10 minutes of training on direction discrimination.

Not only was the sensitivity to direction discrimination significantly improved, but the time to discriminate the direction of movement was reduced significantly for both inefficient and efficient readers,  $p < 0.001$ . The average duration to complete the task (10 pattern contrast thresholds) for both inefficient and efficient readers was reduced from an initial duration of 15 minutes down to 7-8 minutes by the second replication for all students in this study.

#### Reading fluency

The central hypothesis driving the current study was that training using MTR therapy is more effective at increasing reading fluency than either no training (aside from the reading program offered by the school) or training in the word game. Inefficient readers trained using left-right movement discrimination (MTR therapy) improved substantially more in reading fluency than did inefficient readers in the two control groups (Figures 5, 6a, and 6b). When the word game was played for 12 weeks in the middle of the motion game, providing

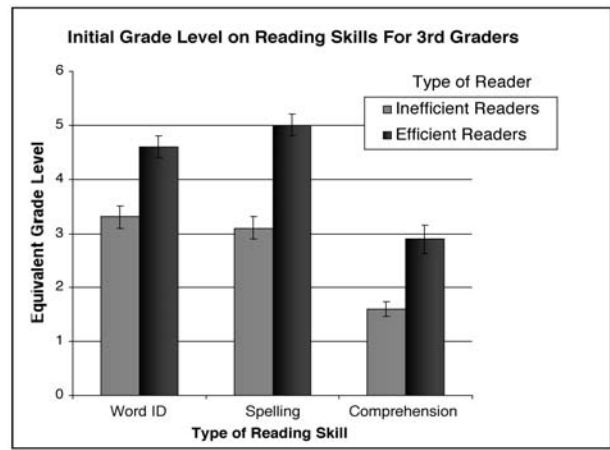
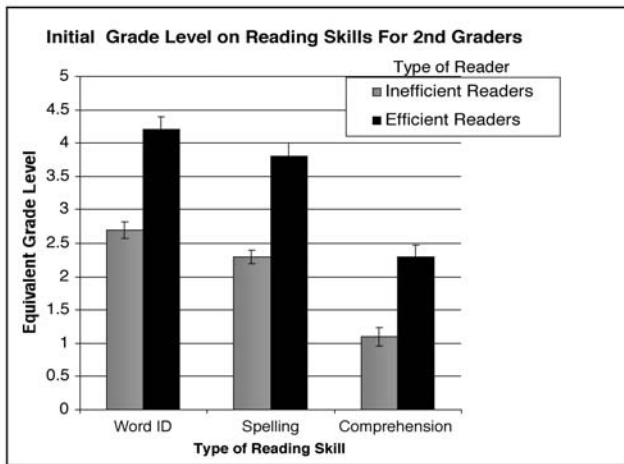


Figure 3. Initial Equivalent Grade Level on the reading skills of Word Identification (Reading Grade Level) and Spelling measured using the WRAT-3, and Reading Comprehension measured using the GSRT for Inefficient Readers (IR) and Efficient Readers (ER) in second grade, Fig. 3a, and third grade, Fig. 3b. The number of students in each group are as follows: Second Grade: 24 IR and 35 ER; Third Grade: 17 IR and 30 ER.

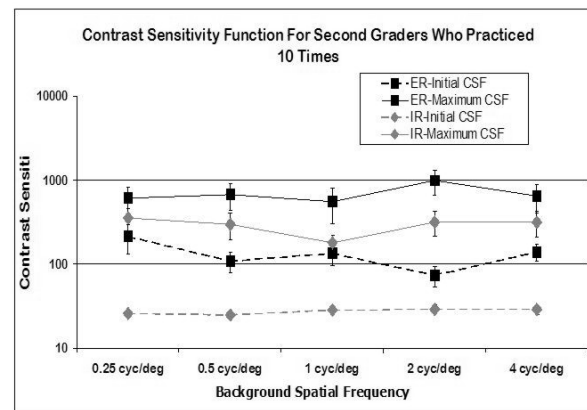
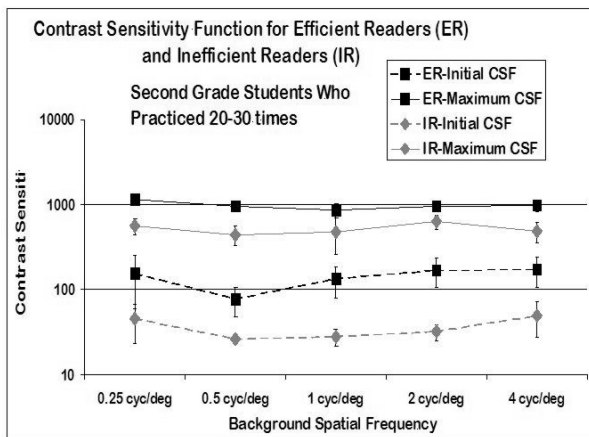


Figure 4. Initial and final mean Contrast Sensitivity Function (CSF) and standard errors from the mean for Inefficient Readers (IR) and Efficient Readers (ER) when discriminating the direction a 1 cyc/deg test pattern moved relative to each of the 5 backgrounds: Figure 4a. When second graders trained on MTR therapy 20-30 times. Figure 4b. When second graders trained on MTR therapy 10 times on average.

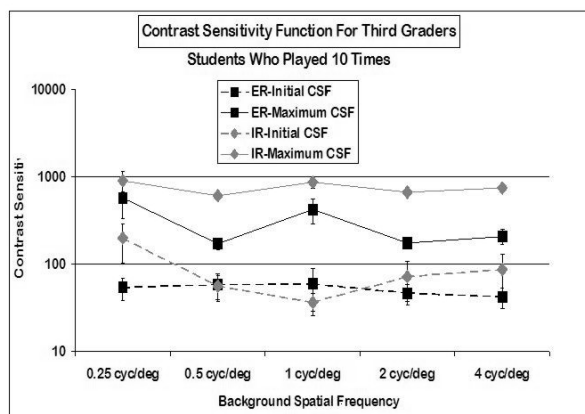


Figure 4c. When third graders trained on MTR therapy 10 times on average. The number of inefficient and efficient readers in each group are listed in Table 1.

a within-subjects design, then reading fluency did not improve for either inefficient or efficient readers (Figure

5). These results were highly significant for both inefficient and efficient readers,  $p < 0.001$ . The more often inefficient and efficient readers were trained on direction discrimination (Figures 6a and 6b) the more they improved in reading fluency. There was a rapid improvement in reading fluency after three-five games, resulting in a 50% improvement in reading fluency, after 10 games, a doubling (two-fold increase) in reading fluency, after 23 games, a three-fold increase in reading fluency for inefficient readers. Efficient readers also improved significantly in reading fluency, doubling in reading fluency after 20-30 games. Inefficient readers improved in reading speed significantly more than did efficient readers in both second and third grade,  $p < 0.001$ , in part, because inefficient readers began at a much slower reading speed than found for efficient readers.



Frequency of Training	CS Improved	Significance Levels	Number of Students
IR Grade 2: 20-30 times	14 fold	***	9
ER Grade 2: 20-30 times	7 fold	***	11
IR Grade 2: 10 times	10 fold	***	9
ER Grade 2: 10 times	5 fold	**	9
IR Grade 3: 10 times	9 fold	***	5
ER Grade 3: 10 times	6 fold	**	11

Table Legend: \*\* indicates  $p < 0.01$ , and \*\*\* indicates  $p < 0.001$ .

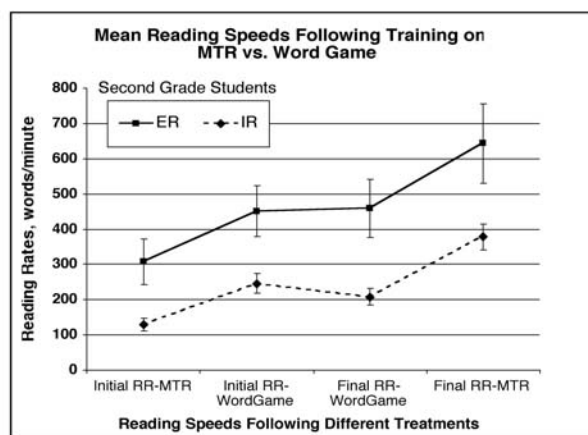


Figure 5. Reading speeds at the beginning, before practicing MTR therapy, right before playing the word game, immediately following the word game, and at the end of the study for second grade students. These results are for 11 inefficient readers and 10 efficient readers.

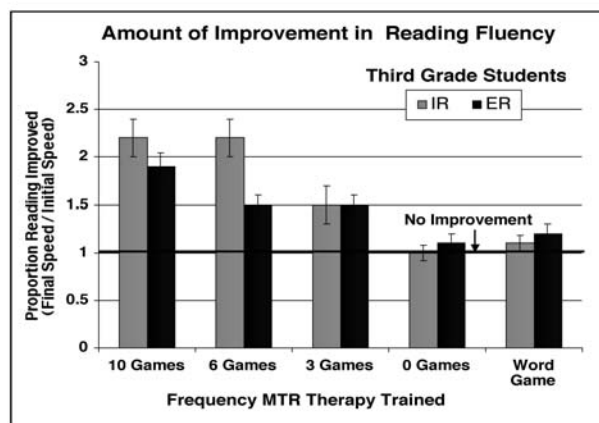
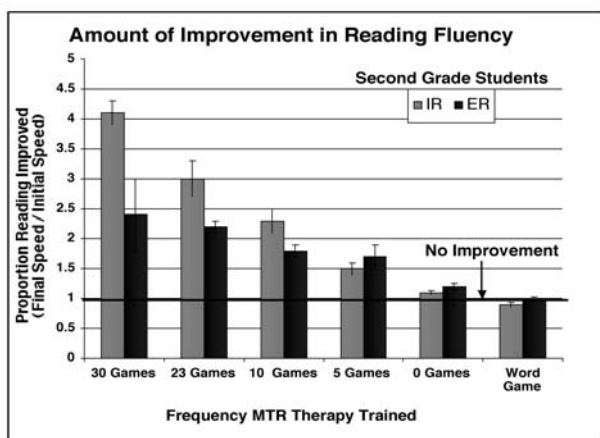


Figure 6. Amount of improvement in reading speeds for Inefficient (IR) and Efficient readers (ER) in second grade (6a) and third grade (6b). The number of subjects in each group are listed in Figure 2. Error bars are standard errors from the mean.

### Other reading skills

Not only did reading fluency improve when students trained themselves to discriminate the direction of motion at low contrasts, but spelling and word identification also improved for inefficient readers in second grade,  $p < 0.001$ , and third grade,  $p < 0.01$ , as shown in Figures 7 and 8. Since two classrooms of second grade students were trained on direction discrimination twice as much as any of the third grade students, the improvements in reading skills for second grade students were an order of magnitude more significant. There were no significant improvements in reading comprehension when measured using the GSRT for either second or third grade students, showing that more global tasks like reading comprehension did not improve when children were trained on MTR therapy only once a week.

### DISCUSSION

Training direction discrimination improved not only a child's contrast sensitivity for movement discrimination, but also reading fluency and a wide range of reading skills. Contrast sensitivity improved dramatically over the course of the training.<sup>24</sup> There was an initial jump in contrast sensitivity after the second replication and then learning showed a gradual improvement (never tapering off) showing that learning continued throughout the full course of training.<sup>24</sup> This same pattern of results was found in this and previous studies. Not only was the sensitivity or gain of directionally-selective pathways increased, but the timing was improved. This suggests that the timing of the motion pathways was improved. Timing deficits, which manifest themselves as an impaired ability to discriminate the direction of motion, represent a core deficiency in inefficient readers. This may result from

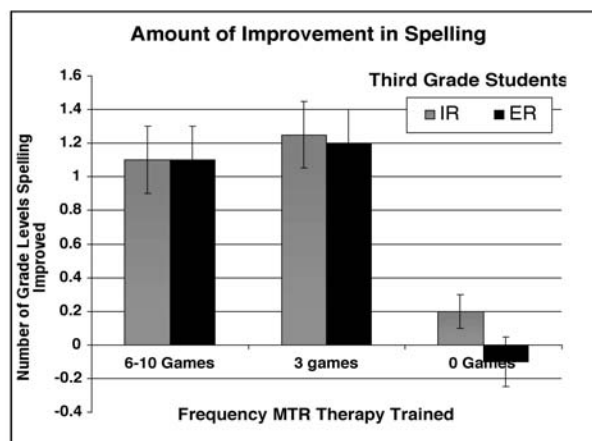
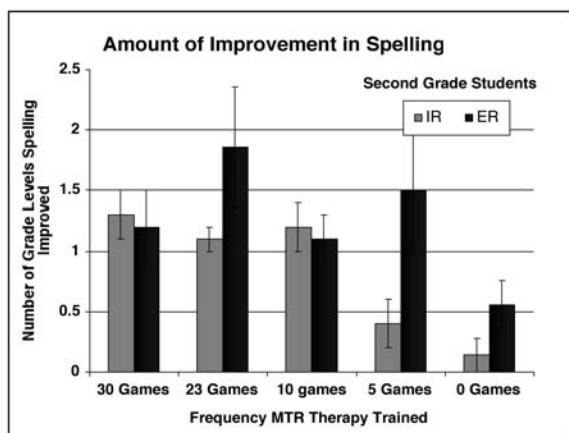


Figure 7. Difference between initial and final **spelling** scores for Inefficient Readers (IR) and Efficient Readers (ER) in terms of the equivalent standardized grade level determined using the WRAT-3 for second graders (Figure 7a) and third graders (Figure 7b). The number of subjects in each group are listed in Figure 2. Error bars are standard errors from the mean.

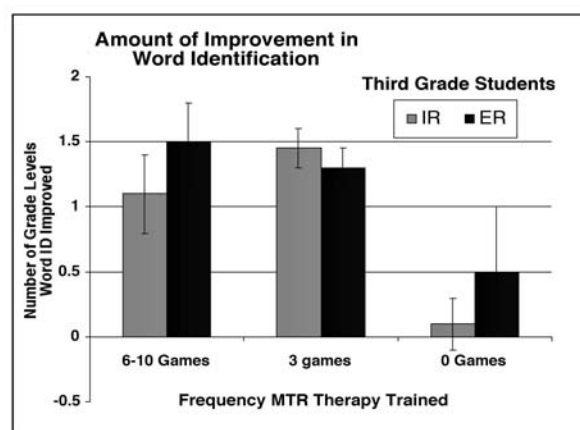
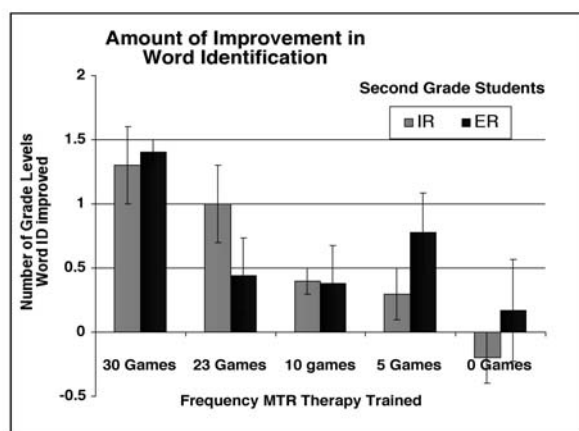


Figure 8. Difference between initial and final **word identification** scores for Inefficient Readers (IR) and Efficient Readers (ER) in terms of the equivalent standardized grade level determined using the WRAT-3 for second graders (Fig. 8a) and third graders (Fig. 8b). The number of subjects in each group are listed in Figure 2. Error bars are standard errors from the mean.

problems in the cortical direction-selectivity network<sup>22-24</sup> arising from sluggish or immature magnocellular neurons<sup>50</sup> which signal the direction of motion.<sup>46</sup>

When the background complexity was systematically increased from a single to a multi-frequency background the contrast sensitivity improved 14 fold for inefficient readers whereas when only sinusoidal backgrounds were used,<sup>24</sup> the CSF improved five fold. Thus, increasing the stimulus complexity improved the CSF three fold more. For efficient readers, however, increasing the stimulus complexity did not increase the amount that the CSF improved.

Previously,<sup>23,24</sup> when only sinusoidal backgrounds were used, smaller improvements in reading fluency were found for both inefficient and efficient readers. Not only were larger improvements in reading fluency obtained when multi-frequency backgrounds were used,

now both efficient and inefficient readers improved significantly more in reading fluency than did students who played the word game or only had the school's reading program.

MTR therapy<sup>22</sup> provides a comprehensive, rapid and effective regimen for remediating reading issues in children. Following the first few sessions, most students learned the direction discrimination task and did not need individual supervision. In fact, most students understood the task after watching the 4-minute QuickTime movie. While traditional vision therapy typically improves eye movements, accommodation and tracking ability, MTR therapy improves an entirely different visual pathway. MTR therapy differs from all other types of vision and educational therapies in that it causes a physiological change in neural timing that enables permanent improvements in the visual channels. Controlled clinical validation studies found that reading speed increased two

to four fold, and comprehension, word identification, and spelling improved one to three grade levels.<sup>23,24</sup> The more MTR therapy was used, the more reading skills improved.

There are different theories accounting for the slow reading speeds that are evident in dyslexia and most agree that it is a multifaceted problem. The most prominent theory is that those with dyslexia have not yet learned phonemic awareness.<sup>2,4,5</sup> However, lack of phonemic awareness can not explain the visual deficits encountered by many dyslexic children. Solan<sup>51</sup> states: "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."

Finding larger improvements in reading fluency when the pattern complexity was increased shows the importance of training direction discrimination using patterns that optimally activate the directionally-selective motion pathways. Finding that the more frequently the child was trained on direction discrimination, the more the child improved in reading fluency indicates that training on direction discrimination is linked to improving reading fluency. This study lends support to the hypothesis that timing deficits represent a core deficit in inefficient readers.

### **Perceptual learning**

Rarely does perceptual learning generalize to a new task. This study, in contrast, demonstrates that training on left-right movement discrimination, when followed by directed reading, leads to significant improvements in reading efficiency (over a grade level on a wide range of literacy skills), as well as two to four-fold improvements in reading fluency. Moreover, tuning up the center of the direction discrimination working range at both low and high levels of visual processing was not only effective, but also much more rapid than competitive therapies<sup>6,11,31,52</sup> to remediate inefficient reading skills.

It is remarkable that practicing MTR therapy results in improvements so quickly when other well documented reading remediation therapies take at least 40 hours. Moreover, most of these reading therapies only remediate phonological deficits and require one-on-one instruction, whereas training on direction discrimination remediates reading skills for children with both phonological and orthographical deficits.<sup>23,24</sup> Other therapies are not only limited to one type of reading deficit, but are also costly to administer. Moreover, on long term follow-up, the group receiving instruction enhanced with FastForWord<sup>19,20</sup> showed no advantages in their reading skills when compared with the group

receiving traditional instruction and with a nonintervention developmental control group.<sup>53</sup> The improvements in reading skills found following direction discrimination training, on the other hand, do not seem to have these limitations. MTR therapy can be administered to an entire class of students in the computer laboratory, as was done in several schools in this study. The remediation appears to be maintained over time.<sup>23,24</sup>

By tuning up low level directionally-selective motion mechanisms using optimal stimuli, it is as though a timing switch was turned on to facilitate learning all reading skills. Phonological language deficits might be remediated by tuning up the lower cortical visual areas which in turn enable the higher language areas to be positively affected. This allowed the entire spectrum of reading deficits to improve significantly. This is supported by finding that the more a child was trained on direction discrimination, the more the child improved in reading fluency.

Training left-right movement discrimination is the first technique that has been found to rapidly remediate a wide range of reading issues. If learning phonological awareness were crucial for remediating reading deficits as proposed by many,<sup>11,19,20,52</sup> then the grapheme is the most important subunit of learning to read. If the grapheme is the crucial element, then training on word discrimination should be more beneficial for remediating reading problems than training on left-right movement discrimination. The results from this study found that inefficient readers did not improve significantly in reading fluency following training on word discrimination, indicating that training phonological awareness is not the only element that requires remediation.

Suppose one were to propose that the improvements in reading fluency found following training on MTR therapy were from improving attention on psychophysical tasks as found when practicing video games.<sup>54</sup> This hypothesis would predict that the word discrimination game would increase reading skills more than training on direction discrimination, since the word game required more attention to complete the task. Moreover, the task was much more closely related to reading than is discriminating the direction a sinusoidal grating moved. Furthermore, in the word game, the words were presented very rapidly in the center of the screen which should have improved reading fluency overall. The most viable hypothesis for the results reported here is that training direction discrimination reduced the timing deficit causing slow reading speeds by improving the gain (contrast sensitivity) and reducing the time to complete the direction discrimination task.



## Cortical plasticity

If magnocellular neurons are a substrate of reading, then one would expect physiological and psychophysical plasticity in channel remodeling to take place at the same time as functional changes in the cortical organization used for reading. Reading involves the coordination of saccadic eye movements, requiring the integration of information from temporal and frontal lobes,<sup>55</sup> and pattern recognition, requiring the integration of information from occipital, temporal and parietal lobes.<sup>56</sup> The temporal lobe shows peak synaptogenesis at 6 to 10 years<sup>57</sup> which corresponds with the time the child is learning to read. Moreover, both temporal and frontal cortical areas continue to develop into young adulthood.<sup>57</sup> Experience refines the output of cortical circuits by introducing patterned activity that fine-tunes the strength of neuronal connections within and among cortical columns.<sup>58</sup> Even in adulthood, brain plasticity results from a continuing process of experience-dependent synaptogenesis.<sup>59</sup> Perhaps, during a time of peak developmental plasticity, as when the child is learning to read, the cortical neuronal connections are especially plastic. It is likely that direction (left-right movement) discrimination is still developing in young children, as shown by this research.<sup>22</sup>

## Training direction-discrimination sensitivity remediates timing deficits

One possible neurobiological mechanism for the timing deficits experienced by inefficient readers<sup>23</sup> is that the sluggish magnocellular (motion) neurons found in the LGN, and cortical areas V1 and the Medial Temporal (MT) cortex of inefficient readers<sup>29,30,50</sup> would make it difficult to attend in a direction discrimination task, since the magnocellular neurons would not signal in advance of the linked pattern or parvocellular neurons (Figure 9). Since magnocellular neurons control the gain of the direction-selectivity network,<sup>46</sup> the more sluggish, immature magnocellular neurons<sup>50</sup> might be causing a deficit in attentional focus, preventing the linked parvocellular neurons from isolating the relevant information. Therefore, the frame of reference would not be demarcated so that the position of the letters in the word, and the words in the text could be read easily. In fact, inefficient readers who are dyslexic have an impaired focus of attention,<sup>60-62</sup> spending a longer dwell time on each word, using an increased number of saccades and regressions to read text that is not due to a deficit in oculomotor control.<sup>63</sup> The large differences between the direction discrimination CSFs for inefficient and efficient readers<sup>22-24</sup> suggest that the direction discrimination network<sup>46</sup> may not yet have developed in dyslexic readers. Perhaps, reading skills are remediated

rapidly following a short amount of training on direction discrimination by increasing the accuracy of figure/ground segmentation.

The inability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time can explain the spatial<sup>13-16</sup> and temporal<sup>17-20</sup> sequencing deficits, as well as the motion discrimination deficits<sup>22-30,64</sup> experienced by most inefficient readers. Improving the sensitivity of inefficient readers to visual motion by training direction discrimination was demonstrated to improve reading deficits of phonological (requiring accurate temporal sequencing) origin. Moreover, children who had both phonological and orthographical (spelling) deficits had the greatest reading deficits and improved the most. These results provide further support that immature magnocellular streams underlie the reading deficits of inefficient readers.

Direction discrimination and not flicker discrimination is the key dependent variable that must be measured to both detect and remediate reading deficits.<sup>23,24</sup> Studies that refute the contribution of magnocellular deficits to explain the mechanisms underlying dyslexia<sup>65-67</sup> are using either flicker detection or discrimination. Neither sensitivity to flicker (counter-phase gratings) nor short duration patterns, is an optimal stimulus for activating direction-selective cells.<sup>46,68,69</sup> Counter-phase gratings required twice as much contrast to detect motion,<sup>69,70</sup> compared to sinewave gratings that moved in one direction. Previous studies of the effects of direction discrimination training on improving reading fluency,<sup>23,24</sup> as well as this study suggest that it is the magnocellular deficits relative to the linked parvocellular activity that provides a method that can be used to reliably identify and remediate dyslexics having both phonological and visual processing deficits.

Moreover, direction discrimination must be done relative to a textured background to encompass the activity of both magnocellular and the linked parvocellular neurons. Motion contrast thresholds requiring both test and background textures are the key metric for direction discrimination.<sup>71,72</sup> This is not true for motion coherence thresholds for random dot patterns which measure motion energy thresholds<sup>73</sup> as used by others.<sup>13,31</sup> Studies that find only a portion of dyslexic readers exhibit motion deficits<sup>13,16,26,64</sup> measured the direction of movement relative to a uniform field instead of a textured background.<sup>40,41</sup> When the contrast sensitivity to the direction of movement is measured relative to a textured background, it is found that all subtypes of dyslexia exhibit motion discrimination deficits.<sup>23-25</sup> When the textured background was composed of multiple spatial frequencies, then reading

fluency improved twice as much as when only single frequency backgrounds were used. These findings provide support that training direction discrimination, presumably by activating magnocellular neurons relative to linked parvocellular neurons increases reading fluency.

Since perceptual learning is gated by attentional mechanisms<sup>74</sup> and inefficient readers had more perceptual learning following training on direction discrimination, this suggests that the deficits in attentional focus experienced by inefficient readers<sup>62</sup> result from an information overload<sup>23</sup> (see Figure 9) and not from an inability to attend from some other source.<sup>61</sup> Training on left-right movement discrimination significantly improved direction discrimination and reading fluency. Improving the gain (contrast sensitivity) and reducing the time to complete the task suggests that this type of training improved the timing within magnocellular streams, so that they more readily bracket the activity of linked parvocellular neurons, thereby reducing the information overload, and improving reading efficiency.

MTR therapy remediates fluency, comprehension, spelling, pronunciation, desire to read, self-esteem and learning. This therapy, which requires minimal frequency and duration of training to produce significant results, is neither language nor reading level specific, and allows for training in the least restrictive environment.

## Conclusions

Additional evidence was provided that a timing deficit is one of the core deficits underlying dyslexia. These results suggest that inefficient readers have immature directionally-selective motion pathways that can be remediated by training direction discrimination. This is the first known reading therapy that remediates the reading deficits of both phonological (requiring accurate temporal sequencing) and orthographical (requiring accurate spatial sequencing) origin. The deficits in reading performance and attentional focus experienced by the inefficient reader are suggested to result from an information overload from timing deficits in the direction-selectivity network<sup>46</sup> that is abated following training on direction discrimination. This study demonstrates that learning direction discrimination is linked to learning to read. The more often direction discrimination was trained, the more reading fluency improved. Training direction discrimination, with reading each day in the classroom, results in faster and more accurate reading skills.

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## Direction Selectivity Signaled By Changes Over Time

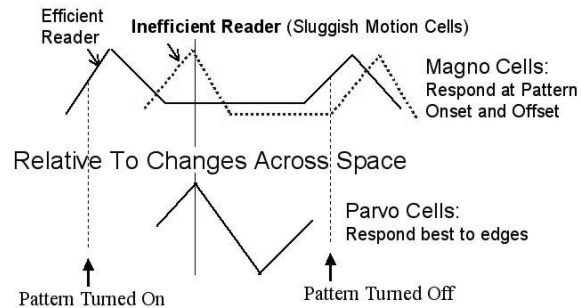


Figure 9. Schematic showing how temporally-based activity of magnocellular neurons (changes over time) brackets the spatially-based activity of parvocellular neurons (relative to changes across space) for efficient readers, and the lack of bracketing for inefficient readers. The magnocellular neurons fire at the onset and offset of the stimulus, whereas the parvocellular neurons transmit the varying contrast over space, i.e. the edge information.

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