Direction-Discrimination Training Improves Reading Fluency in Dyslexics and Provides Evidence that Dyslexia Results from Magnocellular Timing Deficits

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Abstract:

This study examined the effects of direction-discrimination training on reading performance in normal and dyslexic second graders. Participants were divided into two groups: Dyslexic and normal readers. Each of these groups was randomly split into three subgroups, each of which used a different training regimen (direction-discrimination, word, and no training). This study found that not only can dyslexic readers be differentiated from normal readers by their significantly lower sensitivity to the direction of movement, but that their motion sensitivity and reading proficiency improved significantly and permanently following a short course (biweekly 10-minute sessions for 15 weeks) of direction-discrimination training. These improvements in reading fluency, comprehension, spelling, and word identification were found only for dyslexics in the subgroup using the direction-discrimination training regimen. Finally, these results provide evidence that timing deficits in the magnocellular pathways underlie dyslexics' poor reading skills.

A child's visual system is maturing rapidly up until the age of 8 (Thatcher *et al.* 1987; Van Sluyters *et al.* 1990), the period when a child is learning to read. There is much cortical plasticity during this period, and age seven is the middle of the developmental period for learning direction discrimination (Lawton, 2000; Lawton, 2008), so the current study focused on second graders, who average seven years of age. Many children have difficulty with reading. In fact, sixty-seven percent of fourth grade students across the nation do not read proficiently (National Assessment of Educational Progress (2007)). Recent research (Vidyasagar, 1999; Lawton, 2000, 2004, 2007) suggests that children who are inefficient readers have timing deficits between their magnocellular (dorsal stream) and linked parvocellular (ventral stream) pathways that prevents efficient reading. While not all inefficient readers are dyslexic, this timing deficit is particularly pronounced in those who are.

Dyslexia is defined as 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) at normal levels (Hofstetter *et al.* 2000). Dyslexia is a multifaceted learning disability that encompasses both pronunciation-based and visual processing-based issues. Until recently, the core problem underlying reading disabilities was assumed to be a phonological processing deficit (Torgesen *et al.* 1994; Stanovich & Siegel, 1994; Shaywitz, 1996). New research (Wolf *et al.* 2000; Wolf, 1991; Denkla & Rudel, 1974) extends this view to incorporate a second core deficit in timing (measured using rapid automatized naming). The speed of naming digits, letters, and objects, is highly correlated with word reading speed. It contributes uniquely to reading ability in grades (McBride-Chang & Manis, 1996; Manis *et al.* 2000), and is a good test to discriminate between efficient and inefficient readers (Wolf *et al.* 2000; Berninger *et al.* 2004; Bowers *et al.* 1988). Slow reading speeds are a hallmark of dyslexia. In fact, the timing deficits in naming speed are better predictors of reading problems than deficits in phonological processing (Wolf *et al.* 2000).

Children with dyslexia are reported to have some combination of spatial (Cornelissen *et al.* 1998; Lovegrove *et al.* 1980; Stein, 1991; Talcott *et al*. 2000; Vidyasagar, 2001; Facoetti *et al*. 2006) and/or temporal (Kimura & Archibald, 1974; Stanley & Hall, 1973; Tallal *et al*. 1993; Temple *et al*. 2003) sequencing deficits, which may cause the letters in words and the words on a page to appear distorted, displaced, or crowded together (Atkinson, 1991). These spatial and temporal sequencing difficulties are believed by some investigators to result from neural timing deficits (Lawton, 2004, 2007, 2008; Lehmkuhle, 1994; Vidyasagar, 1999, 2001; Wolf *et al.* 2000; Stein, 2001). Dyslexic readers also show motion discrimination deficits, including an impaired ability to discriminate both the direction (Lawton, 2000, 2004, 2007, 2008; Ridder *et al.* 2001; Slaghuis & Ryan, 1999, 2006; Fischer *et al.* 2000) and the speed (Eden *et al.* 1996; Demb *et al.* 1998) of visual patterns. Timing deficits manifest themselves as an impaired ability to discriminate the direction of motion (a core deficiency in inefficient readers as stated above) and may result from problems in the cortical direction-selectivity network (Lawton, 2000, 2004, 2007), which is the V1 (striate cortex) – MT (Medial Temporal cortex) loop that is composed of predominately magnocellular neurons (Maunsell *et al.* 1990; Maunsell & Van Essen, 1983; Merigan & Maunsell, 1990). Magnocellular neurons, which have large axons and dendritic arbors, however, are not sufficient by themselves for direction selectivity (DeValois et al. 2000; Lawton, 2007). Parvocellular neurons, which have small axons and dendritic arbors, are necessary as well. Magnocellular neurons, which signal pattern onset and offset, are excited by low spatial frequency, high temporal frequency, and low contrast patterns **relative to** parvocellular neurons, which analyze the detailed pattern information in the object of interest, and are excited by high spatial frequency, low temporal frequency, and high contrast patterns. In analyzing low spatial frequency information, magnocellular neurons provide a global description of an object, *e.g*. its overall shape and its location; parvocellular neurons provide the local details so that the letters in a word can be deciphered. Since parvocellular functioning among dyslexics is the same as in normal controls (Lovegrove *et al.* 1986; Sperling *et al.* 2003), high contrast thresholds for direction discrimination in dyslexics reveal the underlying deficit in the magnocellular pathway: A normally functioning magnocellular pathway is sensitive to *low-contrast* patterns; high contrast thresholds indicate a malfunction. All dyslexics show deficits in direction discrimination tasks only when textured background patterns are used (Ridder *et al.* 2006; Lawton, 2007). Textured, as opposed to untextured background patterns require figure-ground discrimination, which requires, in turn, normal functioning of *both* the magnocellular and parvocellular pathways. Both motion (magnocellular) and pattern (parvocellular) sensitive neurons must be activated to reveal the underlying direction discrimination deficit inherent in dyslexia. Furthermore, the magnocellular and parvocellular activations must be synchronized for normal processing to occur. It is the lack of synchronization in timing between magnocellular and parvocellular activations, caused by sluggish magnocellular neurons (Livingstone *et al.* 1991; Lehmkuhle *et al.* 1993), that prevents effective pattern analysis and figure-ground discrimination and hence prevents efficient reading (Lawton, 2004, 2007, 2008; Vidyasagar, 1999). Furthermore, it is the exquisite timing between magnocellular and parvocellular activations that enables sequential processing to be done effortlessly, *e.g.* without excessive regressive saccades (Vidyasagar, 1999, 2001).

Several results suggest that reading fluency can be improved by training that focuses on the magnocellular pathway. In particular, Solan *et al.* (2004) 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.* in using a shorter training regimen (20 minutes per week, over 15 weeks) comprising a more focused set of tasks (exclusively left-right direction 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 (Lawton, 2000, 2004, 2007, 2008). It is notable that when dyslexic readers were trained using elementary direction discrimination tasks, a wide spectrum of reading skills improved significantly (Lawton, 2004, 2007), including fluency, reading speed, comprehension, word identification, and spelling. This finding is remarkable, since perceptual learning rarely generalizes to a new task (Fiorentini & Berardi, 1981; Ball & Sekuler, 1987; Sagi & Tanne, 1994).

The current study sought to assess more carefully the effectiveness of the direction-discrimination training regimen (described below) in improving reading fluency**.** Specifically, for both dyslexic and normal second grade readers, the reading improvements produced by each of three training regimens were compared: 1) training in left-right movement discrimination (in addition to the school's regular reading program), 2) training in a word discrimination (in addition to the school's regular reading program), and 3) null training, in which participants received no training other than the school's regular reading program. Standardized literacy tests were administered before and after the training regimens to evaluate their effectiveness in improving reading skills. The current study was also designed to provide a baseline for subsequent direction discrimination studies that increased the levels of complexity by systematically increasing the complexity of the background. Increasing the background complexity in these subsequent studies (Lawton, 2007) made the training more engaging, providing significant improvements for both efficient readers as well as those who are dyslexic.

Methods

Personnel

Eleven UCLA pre-optometry students were recruited to serve as research assistants. None were aware of the goals of the project. At the outset of the study, each research assistant was trained with both verbal and written instructions to administer all of the standardized literacy tests used before and after training. Each research assistant was also trained to show QuickTime movies in administering the reading-speed assessment as well as the direction-discrimination and word training described below. To remove bias in favor of the direction-discrimination training, information describing the techniques being used was not made available to the research assistants until after the study was completed. That information is now available on the website www.pathtoreading.com. Six research assistants were used exclusively to administer tests before and after training. The other five were involved in both the training and testing phases of the study. In addition, three optometrists were employed at the start of the study to test the visual functions of all participants.

Subject Selection

The current study involved 107 second-grade students recruited from 4 public elementary schools in Santa Monica and Los Angeles, California. All children in participating classrooms who returned the IRB-approved, informed consent forms were included, provided they had no known visual or neurological deficits. All were 2nd graders, averaging 7 years old. As discussed below, the Dyslexia Determination Test (DDT) was used to partition the 107 children into a group of 75 normal readers and 32 dyslexics.

The 75 normal readers were randomly assigned to the three treatment groups of sizes 22 for word training, 26 for null training and 27 for direction-discrimination training. The 32 dyslexics were also randomly assigned to the three treatment groups under the constraint that children in each classroom were represented in the intervention of interest: direction-discrimination training. Only children in mainstream classrooms were used; in particular, no children who were already in reading resource programs were included, since the time period for training on direction discrimination was the same time period children were participating in the reading resource program. Teachers confirmed that each child in the study had at least normal intelligence.

Our expectation, based on pilot studies, was that direction-discrimination training would be more effective than the other training regimens in improving reading ability; thus, it was anticipated that the current study would be of most benefit to the participants if most of them received training in direction discrimination. Therefore, to make this intervention worthwhile to the participating schools, more dyslexics were assigned to the direction-discrimination training group (18 students) than to the other two groups (7 students in each group).

Reading skill measures

Students were divided into two groups, dyslexic and normal readers, using the Dyslexia Determination Test (DDT), which is also a test of reading fluency. The reading fluency of every student was assessed both initially and at the end of the current study using the following standardized tests: 1) Gray Silent Reading Test (GSRT); 2) Wide Range Achievement Test (WRAT-3) reading (word identification) subtest; and 3) WRAT-3 spelling subtest. A computer-based reading speed assessment (see below) that was independent of the reader's rate of speaking was also used. In addition, to measure phonological processing, the Comprehensive Test Of Phonological Processing (CTOPP) Rapid Digit subtest; the CTOPP Rapid Letter subtest, CTOPP Rapid Color subtest, CTOPP Rapid Object naming subtest, the Woodcock Johnson Word Attack subtest, and the Lindamood Auditory Conceptualization (LAC) test were used as well.

The intervention of interest, direction-discrimination training, was hypothesized to improve reading fluency. To assess reading fluency, the current study used a reading rate assessment procedure that was limited by a reader's ability to see and process words, but not by his/her speaking rate. In this test, continuous, non-repeating lines of text from the *Frog and Toad* series by Arnold Lobel (interesting, easy-to-read stories at a second grade level) were presented on a computer display six words at a time for an interval controlled by a staircase-adjustment procedure. *Frog and Toad* text was used so that: 1) the story was meaningful, 2) different portions of text had same level of difficulty, and 3) children saw novel, entertaining material each time they correctly read the six words on the screen.

The child was told to read the words and speak them to the experimenter. Although the child had a limited time to read the words, they could be spoken both while they were being displayed, and after the words had been removed from the display. Once the words had been read correctly, the research assistant pressed a button that provided positive feedback for 500 ms, in the form of a black plus sign, which appeared just above where the text was presented, and a score in the upper right corner of the window. The feedback was followed by the display of the next set of six words. If the child made an error, speaking one or more words incorrectly, the research assistant provided a correction, and the same six words were shown again. However, the child was now asked to repeat only the words missed in the six words of text. The same phrase was only shown 2 times in a row, so that difficult phrases were not a stumbling block in this task. Just six words were displayed at a time so that there was no crowding from adjacent words above or below the line being read, and at least two saccades were required to read each line. The text was rendered using large (0.5 cm wide by 0.5 to 0.75 cm high) white (100 cd/m^2) *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 of luminance 50 cd/m^2. The child was seated 57 cm from the display.

At the start of the procedure, the six words were displayed for 9 seconds, corresponding to a rate of 40 words per minute. A two alternative forced-choice (2AFC) double staircase procedure configured to measure 79% correct responses was used to adjust the presentation time, and thus reading rate, as each successive line of six words was presented. Starting from the initial value of 40 words/min, reading rate was increased by 1 step (12%) only when five out of six words were read correctly and in the correct order. After an error, the reading rate was decreased by 1 step. After the first error, the 2AFC staircase procedure was initiated. The presentation interval was lengthened (reading speed decreased) until three successive lines of text were read correctly. Then the presentation interval was reduced (reading speed increased) until an error was made. This process continued until 6 reversals in reading speed were obtained. The mean reading-speed threshold was then computed from two threshold measurements, each threshold being the mean of the last 3 out of 6 reversals in reading speed. The child took about 10 minutes to complete the reading rate assessment.

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 (Griffin & Walton, 1987). Boder (1973) 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) both dysphonetic and dyseidetic. The DDT is based on Boder’s[37] differentiation of dyslexic children into the 3 subtypes above that can be used for rapid diagnosis of the type and severity of dyslexia. The DDT and the Decoding Encoding Screener for Dyslexia (DES-D), a related standardized test, are the only tests available that provide a measure of the type and severity of dyslexia.

As stated above, the DDT was used to classify each student as a dyslexic or normal reader. The DDT requires the child to read 10 words (5 with irregular spelling and 5 with regular spelling) at each grade level, beginning at pre-kindergarten. Once 6 out of 10 words are read incorrectly, then the next lower grade level is taken as the reading (decoding) grade level. The child is then asked to spell 10 words correctly for an eidetic challenge; these are words that they pronounced correctly in less than 2 seconds. Finally the child is asked to spell 10 unknown words the way they sound, *i.e.* phonetic equivalents (‘laf’ for ‘laugh’) for a phonetic challenge. The number of words spelled correctly and the reading grade level are used to determine the child’s classification: Above Normal, Normal, Borderline Normal, Mildly Below Normal, Moderately Below Normal, and Markedly Below Normal, in terms of either decoding (pronunciation) or encoding (spelling). Readers were classified as dyslexic if their DDT scores fell in any of the categories from Borderline Normal down to Markedly Below Normal. Children who read at or above grade level can be diagnosed as dyslexic if they have sufficient difficulty spelling words at their grade level or writing them the way they sound. Thus, even though they were recognizing words at grade level, some of our subjects were classified as dyslexics because they failed further challenges in spelling and pronunciation tested using the DDT. Being classified as dyslexic was validated by other standardized tests of reading skills.

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 a stumbling block in reading fluency.

Testing Procedures

Standardized tests were administered as follows, both prior to and following training. The children cycled through different computer stations one at a time, each tended by a different research assistant. At each station one to two tests lasting collectively about 10 minutes, were administered. For example, the WRAT-3 reading and spelling subtests were administered at one station. The GSRT was the only test that was administered to small groups of participants, being timed for 15 minutes.

The raw score on each reading skills test corresponded to a standardized equivalent grade level, where a grade level of 1 is composed of students averaging six years of age, grade level 2 of students averaging 7 years of age, and so forth. Initial and final reading scores and measures of improvement on each of the psychometric literacy tests were reported in terms of equivalent grade level since this is the most relevant information for teachers, school administrators, and parents. 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.

Training Procedures

After the standardized tests were administered to all participants, each student was assigned to one of the six groups, three groups of dyslexics to receive training in either direction discrimination, word discrimination, or no training outside of the school's regular reading program, and three corresponding groups of normal readers. Students in each of the direction-discrimination training and word-training groups were pulled from class to do this training for ten minutes twice per week, always between 8:15 and 10:10 AM. This provided each child substantial opportunity, following training, to practice reading during the school day. (Each second grade class had at least 60 minutes of directed reading each day.) The training, which started in January and finished in May, continued for 15 weeks, although not always consecutively due to holidays and planned school activities. Students in the null training group were not pulled from class. Computer training was conducted in the classroom in 3 of the 4 elementary schools, and in the computer lab in the remaining school. In the classroom computer training, there was one research assistant for each 1 or 2 students, while in the computer lab there were 5 research assistants for the approximately 20 students.

iMac computers, were used for training in all 4 schools, and the contrast and brightness of each computer screen was calibrated using a Spectra Pritchard 1980A photometer. Students in the direction discrimination and word training groups received instruction by watching a four-minute QuickTime movie augmented by verbal instruction from the research assistant when needed. Finally, research assistants made sure participants sat an arm's length, about 57 cm., from the screen, and kept their eyes focused in the middle of the screen.

Training Tasks

Direction-discrimination training (present tense changed to past tense)

Direction-discrimination training used displays (see Fig. 1) comprising a stationary, central window, surrounded by a stationary, vertically oriented sine wave grating of spatial frequency $w_{\mathbf{background}}$ (Lawton, 2000). The window contained a vertical sinusoidal test grating of spatial frequency $\mathbf{w_{test}}$. A given trial comprised three frames, each lasting 150 ms. The phase of the test grating in frame 1 was ±45°, chosen randomly, relative to the cosine phase in the middle of the screen. On each of frames 2 and 3, the test grating phase shifted 90° in a fixed direction (either rightward or leftward). The task of the trainee was to indicate the direction of movement using the right or left arrow key. A brief tone was presented after incorrect responses.

At the start of a session, both the test and background gratings were set to 5% contrast. Each time the child correctly identified the direction the test grating moved, the contrast of the test grating was lowered until the child made an incorrect response. The step size varied from 0.3% down to a step size of 0.1% at 0% contrast. Very low contrasts were obtained by special modifications to the color lookup table, varying only one color gun at a time. Although these manipulations might be expected to lead to hue heterogeneities in the stimuli, they are not visible, and moreover, it is well documented that judgments of motion direction in very low contrast stimuli depend only on luminance variations (*e.g*. Lu & Sperling, 1995). Following the first incorrect response, a double-staircase procedure (Lawton, 1984) was used to estimate the direction discrimination contrast thresholds. Each error increased the test grating contrast by one step. The staircase terminated after 6 reversals, and the mean of the last 3 was taken to estimate contrast threshold. If the last 3 reversals, where the threshold value should be leveling off, contained 4 or more increments in contrast, the threshold was considered too variable to be reliable, and the contrast threshold was automatically re-measured by the computer. Using the last 3 of 6 contrast reversals was found previously to provide the most reliable results compared to using larger numbers of contrast reversals (Lawton, 1984). Three successive correct responses reduced test grating contrast by one step. This staircase procedure estimates the contrast needed for 79% correct responses.

In a given staircase run, the center spatial frequency, w_{test}, was either 0.25, 0.5, 1, or 2 cyc/deg, and surround grating spatial frequency, $w_{background}$, was 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 required 20 threshold determinations (*i.e.* one for each of the four test spatial frequencies paired with each of the five background spatial frequencies, progressing from 2 octaves below to 2 octaves above the test spatial frequency).

In the current study, each session covered half a training cycle, consisting of 10 threshold determinations: one threshold for each of two ‘test’ frequencies set against each of five background frequencies. In the first session of each of the 15 weeks of the study, all thresholds involving test spatial frequencies 0.5 and 1 cyc/deg were measured. In the second session of each week, all thresholds involving test spatial frequencies 2.0 and 0.25 cyc/deg were measured. Each session took about 10 minutes to complete. At the end of each staircase run, the trainee received a score to increase motivation: The lower the contrast threshold, the higher the score.

The stimuli used for training on left-right direction discrimination (see Fig. 1) were previously found to be optimal for measuring the sensitivity of directionally selective motion pathways (Lawton, 1984, 1985, 1989). The procedure for determining optimal activation of directionally selective motion pathways was as follows:

1. Sinewave gratings (activating both low and high levels in the motion pathways) were used, instead of random dots that activate only high levels in the motion pathways, *i.e.* MT and above (Zohary *et al.* 1994). Perceptual learning is over 10-fold faster when discriminating the direction of sinewave gratings (Fiorentini & Berardi, 1981) than for random dot patterns (Ball & Sekuler, 1987).
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 (Lawton, 1984).
3. A range of test frequencies (0.25, 0.5, 1, and 2 cyc/deg) was used to span the spatial frequencies that predominantly activate motion pathways (Kaplan & Shapley, 1986; Merigan & Maunsell, 1990; Legge, 1978).

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 each channel's spatial frequency tuning function. These background frequencies are an octave apart, since neurons in the direction-selectivity network are tuned to approximately one octave (Merigan & Maunsell, 1990; De Valois *et al*. 2000), and perceptual learning of direction discrimination does not transfer to spatial frequencies differing by more than one octave (Fiorentini & Berardi, 1981). Increasing the background structure by using multiple spatial frequencies, having a low fundamental frequency and a difference frequency equal to the test frequency, increases the contrast sensitivity (the inverse of the contrast threshold) of movement discrimination for a wider range of background patterns than found with single frequency backgrounds (Lawton, 1985).
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 (Kaplan & Shapley, 1986).
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 (Sclar, Maunsell, Lennie, 1990).
7. To prevent the involvement of saccades, 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 (Westheimer, 1954). This design also prevented express (fast) saccades (Carpenter, 2001) from contributing to direction discrimination.

Word training

One group of dyslexics and one group of normal readers (control groups) were trained in a word discrimination task twice a week, each session lasting around ten minutes. There were 3 different word games, each played on a separate day. The instructions for each word game appeared in writing at the beginning of the word training. All words were in lower case letters. The first word training game was the animal game, in which the student pushed the right arrow key if the word was an animal name, *e.g.*, “bird”, and the left arrow key otherwise. The second word training 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. The third word training 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 student 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; then the word disappeared, a ‘+’ or ‘-‘ appeared above the location of the word, too indicate “correct” or “incorrect,” respectively, and the score was displayed in the upper right corner of the window. The faster the child responded, the faster the words were presented. This test was timed for 10 minutes and stopped automatically when the time was up.

The word discrimination training provided a computer-based task requiring attentive processing for an equal amount of time as the direction-discrimination training. The word training provided a control that trained reading pathways that rely more heavily upon the pattern system (ventral pathways), *i.e.* recognizing and categorizing words, rather than the motion system (dorsal pathways).

Results

The DDT classified 20 dyslexics as having borderline dyslexia and 12 dyslexics as having mild dyslexia, but all struggled with reading. Based on the DDT, there were 22 children who were classified as dyseidetic, 6 children classified as dysphonetic, and 4 children who were both dyseidetic and dysphonetic. Since children in the current study were in second grade, the time period when they were learning to pronounce syllables and words, and most of the dyslexics in the current study were dyseidetic, having no problems with pronunciation, there were no significant differences between direction-discrimination training and control groups on tests of phonological processing.

Before training, dyslexics read significantly more slowly, 121 ± 7 words/minute, than normal readers, who read 235 ± 13 words/min. (see Table 1). Before training, although both dyslexic and normal readers scored at or above grade level on tests of sight-word recognition and spelling, normal readers scored an average of at least one grade level above the average dyslexic reader (see Table 1). As revealed by t-tests, the differences between dyslexic and normal readers on all reading-skill measures were significant (see Table 1). Moreover, comparing differences between the dyslexics in each of the three training regimens at the beginning of the current study with one-factor ANOVAs showed that there were no significant differences. Furthermore, a t-test comparing the initial reading speeds of the 18 dyslexics trained in direction discrimination to the 14 dyslexics in the pooled control groups found no significant differences. These statistical tests show that the direction discrimination and control groups of dyslexic students were matched samples.

(Insert Table 1 about here)

Direction Discrimination Sensitivity

Figures 2a-d show how direction discrimination sensitivity improved with training for both dyslexic and normal readers across all test and background spatial frequencies. This improvement was highly significant for dyslexics as shown by a within-subjects two-factor ANOVA, which assessed the influence on movement sensitivity of (1) replication number, and (2) target spatial frequency, and averaging over background spatial frequency ($F(14,42)=9.68$, $MSE=505.67$, $p<0.001$) for dyslexics and ($F(14,42)=19.66$, $MSE=1397.29$, $p <0.001$ for normal readers). Fifteen replications were examined for each of 4 target spatial frequencies, which were surrounded, in turn, by each of five different backgrounds, for a total of 20 pattern combinations. Fig. 2a gives the results for test frequency 0.25 cyc/deg, and Figs. 2b, 2c, and 2d give corresponding results for test frequencies of 0.5, 1.0, and 2.0 cyc/deg. Black lines show results for normal readers, and gray lines results for dyslexics. Dotted, dashed and solid lines show the mean contrast sensitivities achieved in the first, second and 15th weeks of training, respectively.

Note that at the start (dotted lines) and end of training (solid lines) normal readers were twice as sensitive to the direction of movement as were dyslexics. Sensitivity to the direction of movement and improvements in contrast sensitivity were highest for 2.0 and 1.0 cyc/deg test patterns, followed by 0.5, and 0.25 cyc/deg test patterns, seen most clearly in Fig. 3. The proportionate difference in the contrast sensitivity of dyslexic and normal readers, both before and after training, was highly significant, $p<0.001$, when analyzed using a t-test for paired sample means to compare each of the 20 pattern combinations, that had been averaged across observers. This difference was especially marked (normal readers were 4-fold more sensitive than dyslexics) for the 2.0 cyc/deg test stimulus when test and background spatial frequencies were equal (Fig. 2d). This test stimulus activates parvocellular neurons more than the other test stimuli do, showing the importance of magno-parvocellular interactions, as is discussed below.

Besides a level difference in sensitivity to direction discrimination, the shape of the Contrast Sensitivity Functions (CSFs) for the 2.0 cyc/deg test stimulus is noticeably different between normal and dyslexic readers. Normal efficient readers have a CSF that is concave downward, while dyslexic readers have a CSF that is concave upward, as found previously (Lawton, 2000, 2008). The shape difference results from direction discrimination being easiest for normal readers, and most difficult for dyslexic readers, when test and background frequencies are equal. This shape difference in the CSF between dyslexic and normal readers indicates that normal readers are facile at figure-ground discrimination, whereas those with dyslexia find figure-ground discrimination to be very difficult. Sinewave gratings provide a more effective stimulus for detecting different levels of reading dysfunction than do random dots, since random dots only reveal a level difference, that can be overlapping, between dyslexic and normal readers (Ridder *et al.* 2001; Solan *et al.* 2004) and reveal no CSF shape difference, as is found using sinewave gratings.

The mean CSF on each replication, when averaged across all observers, both dyslexic and normal, is plotted in Fig. 3 to show the average amount of improvement of the group as a whole. For all test and background frequencies, contrast sensitivity improves over the course of the full 15 weeks of training, with normal readers tending to show more improvement, an average of 7-fold, than dyslexics, who improved an average of 5-fold. Figure 3 gives full learning curves for each of the four test spatial frequencies f = 0.25, 0.5, 1.0 and 2.0 cyc/deg. For a given test frequency f, the ordinate gives the mean contrast sensitivity (averaged across all background frequencies) achieved in week j of training, for j = 1, 2,…, 15. Individual subjects did not show monotonic increases as shown in the graphs in Fig. 3, since on some days they paid more attention to the task, obtaining better contrast sensitivities than on days when they were tired or did not eat good breakfasts. The mean contrast sensitivity to discriminate direction increased significantly for all 4 test frequencies as the training progressed. There is an initial jump in contrast sensitivity after the second replication, followed by a roughly constant, incremental improvement throughout the full course of training. After the second replication the time to complete the task was reduced by half (Lawton, 2007).

In another controlled-validation study (Lawton, 2007), subsequent to the present study, multifrequency backgrounds, which provided a more structured frame of reference for judging the direction of movement (Lawton, 1985, 1989), were used in addition to pure sinewave backgrounds. Dyslexics in that study were more attentive to the training task, their CSFs improving an average of 14-fold instead of only 5-fold. The subsequent study, which substantially increased the size of the dyslexic sample to 41 (40 were dysphonetic) second and third graders, found that only when dyslexics were trained in direction discrimination relative to textured backgrounds (sinusoidal or multifrequency) did reading fluency improve, as found in the current study. Furthermore, the more dyslexics were trained in direction discrimination, the more their reading speeds improved (Lawton, 2000, 2007, 2008).

Reading Skill

The central hypothesis driving the current study was that direction-discrimination training is more effective at increasing reading fluency than either no training (aside from the regular reading program offered by the school) or training in word discrimination. This was confirmed, as shown in Fig. 4. A two-factor ANOVA with post-training reading fluency as the dependent variable was used to investigate this hypothesis. The factors included in the model were Reading Skill Level (dyslexic vs. normal reader) and Training Regimen (direction-discrimination training, word-training, vs. no training); to increase power, the model also included a covariate: For each child, the covariate was the difference between that child's initial reading fluency and the mean initial reading fluency of their Reading-skill cohort. For a dyslexic reader, for example, the covariate was that reader's initial reading fluency minus the mean reading fluency taken over all dyslexics in the study.

This ANOVA revealed significant main effects of Reading Skill (F(1,102)=104, MSE=44202, $p < 0.001$) and also of Training Regimen (F(2,102)=5.54, MSE=23704, $p < 0.005$). Interpretation of the main effects is complicated, however, by the fact that there was also a significant interaction between Reading Skill Level and Training Regimen (F(2,102)=5. 34, MSE=22836, $p < 0.006$).

The source of this interaction is revealed in Fig. 5, which plots the estimated marginal mean final reading speeds. The heavy dashed line gives the estimated final reading speeds for dyslexic readers, while the heavy solid line gives the estimated final reading speeds normal readers. The straight, dashed and solid lines give the mean initial reading speeds for the dyslexic and normal readers, respectively. Note that all three groups of normal readers showed significant increases in reading speed over the course of training. However, among dyslexics, only those who received training in direction discrimination showed significant reading speed improvements. The significance of a contrast that compared the final reading speeds of the dyslexics trained in direction discrimination with the final reading speeds of the dyslexics in the two control groups was evaluated. This yielded an F(1,102) ratio of 15.65 ($p < 0.001$). The corresponding contrast for the normal readers was not significant; their average improvement in reading speed was 48%. On the other hand, when multifrequency backgrounds were used in the subsequent study mentioned above (Lawton, 2007), providing training on figure-ground discrimination over a wider range of background patterns (Lawton, 1985, 1989), normal readers who were trained in direction discrimination improved significantly more than did those trained in word discrimination or who had no training beyond the school's regular reading program.

The increase in reading speed for dyslexics in the direction-discrimination training group, when averaged across all subjects was 101%. Concealed in this average is the fact that most (11 out of 18) of the dyslexics trained in direction discrimination at least doubled their reading speeds, while the remainder improved at least 50%. In the subsequent study mentioned above, when multifrequency backgrounds were used in addition to the sinewave backgrounds used in the current study (Lawton, 2007), reading speeds of dyslexics in the direction-discrimination training group increased an average of 4-fold instead of 2-fold. The average improvement for the other two groups of dyslexics was not significant at 18%.

One might wonder whether the connection between Reading Skill Level and Training Regimen is due to the fact that the reading fluency of normal readers is saturating and thereby suppressing the differences in improvement between the different training regimens. This is not likely the case. Proficient readers frequently obtain reading fluencies of 1200 words per minute (corresponding to display durations of 300 msec per 6 word display) (Rubin & Turano, 1992; Latham & Whitaker, 1996). The mean reading fluency of our normal readers following training was 327 words per minute (corresponding to a display duration of 1100 msec per six word display). Thus, even the normal readers had substantial room for improvement.

In summary, the significant connection between Reading Skill Level and Training Regimen reflects the fact that the three training regimens produced similar improvements in reading fluency for normal readers, while direction-discrimination training was the only training regimen that significantly improved the reading fluency of dyslexics. Indeed, the significant main effect of the direction-discrimination training regimen is the improvement in reading fluency shown by dyslexics trained in direction discrimination as contrasted with the dyslexics in either control group, who barely improved at all.

The lack of any significant effect of training regimen for normal readers in our primary dependent variable, final reading speed, suggests that this group is also unlikely to show significant effects for any of the other measures of reading skills. To verify this, t-tests were used to compare the improvement of the direction-discrimination training group of normal readers on each of the measures of reading skills with the average improvement shown by the pooled control groups of normal readers. As anticipated, none of these tests revealed statistically significant differences in improvement (even without Bonferroni adjustment) between the normal readers in the direction-discrimination training and pooled control groups of normal readers.

The corresponding results for dyslexics found significant improvements in reading skills only for those trained in direction discrimination. For each reading competence measure, t-tests compared the improvement shown by dyslexics trained in direction discrimination versus dyslexics in each of the control groups. Results are shown in Tables 2 and 3. Low p-values were obtained for GSRT Reading Comprehension, DDT Reading, WRAT-3 Spelling, and WRAT-3 Reading, which were highly significant with a Bonferroni adjustment of 0.0125 (= 0.05/4). Tests of phonological processing showed no significant differences between groups, which would be expected with this population of students, who were primarily dyseidetic dyslexics. Therefore, tests of phonological processing were not used to determine the Bonferonni adjustment.

(Insert Tables 2 and 3 about here)

Given their striking improvements in reading speed following training, it is not surprising that dyslexics trained in direction discrimination improved significantly more in reading comprehension than did dyslexics in the control groups. This is predictable, since the GSRT is a timed test of reading comprehension, a test whose performance would be expected to improve with increased reading speed. The DDT Reading test also has a timed component likely to show improvement with increased reading speed. Moreover, the improvement on the DDT was significantly more than found on the WRAT-3 Reading subtest, supporting the importance of using a test of reading grade level having a timed component. The improvement in spelling, which depends on sequential processing of letters, also was significant only for dyslexics in the direction-discrimination training regimen, even though children trained in word discrimination practiced learning spelling one-third of the time in the Nonsense word game.

Because the DDT was the tool used to partition our subject pool into dyslexic and normal readers, general improvement in the post-training DDT scores of our dyslexics simply as a result of regression to the mean was anticipated. However, as the t-test (Table 2) and the mean grade level improvement (Table 3) reveal, the improvement was only significant for the direction-discrimination training group, improving over a grade level on the DDT, whereas dyslexics in the other training groups did not improve on the DDT. A detailed look at the performance on the DDT of the 18 dyslexics in the direction-discrimination training group reveals the following: by the end of the study 16 had normal or above normal reading skills, and the other two (one dysphonetic and one dyseidetic) had both improved from mild to borderline dyslexia.

One class of second graders at John Muir Elementary School participated not only in the current study, but in the subsequent study mentioned above (Lawton, 2007) when they were in third grade. These results show that the more dyslexics were trained on direction discrimination, the more they improved in reading fluency, including reading speed, comprehension, spelling and word identification (see Fig. 6). These results demonstrate that improvements in reading fluency are maintained over time, and the more a child is trained in direction discrimination, the more reading fluency improves.

Discussion

The current study found that training in direction discrimination for 10 minutes twice a week for 15 weeks significantly improved the reading fluency and comprehension of dyslexic second graders. On the other hand, no significant improvements were observed for dyslexic readers who were trained in discriminating between different categories of words, or who received only the school's regular reading program. This is particularly interesting in light of the fact that the severity of dyslexia in the current study was borderline or mild, and yet only children trained in discriminating the direction of movement improved in reading fluency, as was also found in the subsequent study (Lawton, 2007), which involved students having both mild and more severe levels of dyslexia. Before training, normal readers were significantly more sensitive to the direction of motion than were dyslexics, showing that dyslexics are impaired in direction discrimination compared to normal controls, as found in other studies (Lawton, 2000, 2004, 2007, 2008).

The current study also found that the direction discrimination CSF measured using sinewave gratings is more effective in differentiating between normal and dyslexic readers, showing *both* a pattern difference (see Fig. 2d) and a level difference (Lawton, 2000, 2008), rather than just the level difference found when discriminating the direction of random dot patterns (Ridder *et al.* 2001; Slaghuis & Ryan, 1999; Solan *et al*. 2004; Cornelissen *et al.* 1998). Moreover, direction-discrimination training is the first known intervention that remediates the reading deficits of both phonological (requiring accurate temporal sequencing) and orthographical (requiring accurate spatial sequencing) origin (Lawton, 2000, 2004, 2007, 2008). A possible mechanism for this is that phonological language deficits are remediated by tuning the lower cortical visual areas which, in turn, enable the higher language areas to function more efficiently, significantly improving the entire spectrum of reading deficits. The rapid perceptual learning that results from direction-discrimination training is remarkable. The significant improvement in reading fluency after only a short amount of direction-discrimination training suggests that the dorsal pathway provides a key role in directing attention for sequential processing, as is required for reading fluency (Vidyasagar, 1999).

A magnocellular deficit in dyslexics is suggested by a substantial body of psychophysical evidence (Lawton, 2000, 2004, 2007, 2008; Livingstone *et al.* 1991; Lovegrove *et al.* 1980; Ridder *et al*. 2001; Slaghuis & Ryan, 1999, 2006; Stein & Walsh, 1997; Stein 1991, 2001; Vidyasagar, 1999, 2001; Fischer *et al.* 2000), as well as evidence from brain imaging studies (Eden *et al*. 1996; Demb *et al.* 1998). Results of the current study support this hypothesis, since prior to training dyslexics had significantly lower contrast sensitivities for discriminating the direction of motion than did normal readers. This lowered direction-discrimination sensitivity is associated with a magnocellular impairment in the entire peripheral visual system, from retina to visual cortex (Stein, 2001), associated with the center of gaze, since both direction discrimination and reading are performed in the neural pathways associated with the central visual field. Moreover, the present study demonstrates that direction-discrimination training improves both the motion sensitivity *and* the reading speed of dyslexics, suggesting that magnocellular timing and sensitivity deficits underlie their reading difficulties.

Data from the current study suggest that dyslexic readers have poorly tuned direction-selective motion pathways, since they had significantly lower direction discrimination sensitivity than do normal readers. Experience refines the output of cortical circuits by introducing patterned activity that fine-tunes the strength of neuronal connections within and among cortical columns (Trachentberg & Stryker, 2001), improving neural timing by increasing the strength of both inhibitory and excitatory connections between magnocellular and linked parvocellular neurons. This suggests, in turn, that the faulty timing of poorly tuned magnocellular neurons may be remediated by direction-discrimination training between patterns that maximally activate the motion pathways (dorsal stream), a suggestion that has been clinically validated in the present, and other studies (Lawton, 2000, 2004, 2007, 2008). These studies further suggest that timing in the dorsal visual pathway is improved by training on left-right direction discrimination, enabling significant, rapid improvements in a wide range of reading skills by allowing the higher cortical areas to function more effectively, as mentioned above.

One possible neurobiological mechanism for these timing deficits is that sluggish magnocellular (motion) neurons found in the LGN and cortical areas V1 and the Medial Temporal (MT) cortex of dyslexic readers make it difficult to attend in direction discrimination tasks, since these magnocellular neurons in the dorsal stream would not signal in advance of the linked pattern or parvocellular neurons in the ventral stream (Lawton, 2004, 2007, 2008). While the timing of visual events in the direction-selectivity network is signaled by biphasic even-symmetric magnocellular neurons, activated at pattern onset and offset, providing the background frame of reference, the detailed pattern information used to identify each word is signaled by monophasic odd-symmetric parvocellular neurons, *e.g.* edge detectors, in layer 6 of area V1 (DeValois *et. al*. 2000). Moreover, Nassi, Lyon, & Callaway *(*2006) have shown that layer 6 neurons constitute both magnocellular and parvocellular inputs that feed *forward* to MT, supporting the direction discrimination model proposed by DeValois *et al*. 2000.

It is reasonable to conjecture that this ability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time is what has been disrupted in dyslexia, resulting in temporal and spatial sequencing deficits that slow reading speeds (Lawton, 2004, 2007, 2008). Since physiological data demonstrate that magnocellular neurons control the gain of the direction-selectivity network (De Valois *et al*. 2000), perhaps the dyslexic reader's more sluggish, poorly tuned magnocellular neurons cause a deficit in attentional focus, preventing the linked parvocellular neurons from isolating and sequentially processing the relevant information needed when reading (Vidyasagar, 1999, 2001; Facoetti *et al.* 2006; Lawton, 2004, 2007, 2008). This conclusion is supported by the finding that only children in the direction-discrimination training group improved significantly in spelling, a task requiring sequential processing of letters. In addition to impairing sequential processing, sluggish magnocellular neurons would also impair figure-ground discrimination, especially when test and background patterns are alike, as pointed out in the Results section and previously (Lawton, 2000, 2008).

The brain systems that control the attentional spotlight have been described as an interconnected network of cortical and subcortical structures which include the prefrontal and posterior parietal lobes, the anterior cingulate gyrus, and the pulvinar and reticular nuclei of the thalamus (Corbetta, 1998; Martinez et al. 2001; Posner & Peterson, 1990). Neurophysiological recordings show strong influences of attention on neural activity in multiple extrastriate areas including retinotopic areas V1, V2, V3A, and V4 as well as regions of the ventral (TEO, TE) and dorsal (MT, MST, posterior parietal lobe) processing streams (Colby, 1991; Motter, 1993). The basic finding has been that stimuli at attended locations elicit stronger discharge in visual neurons responsive to those stimuli than do the same stimuli when attention is directed away from their location. Both the timing and strength of attention effects in different cortical areas support a feedback mechanism whereby attentional amplification, first occurring in higher areas, is projected back to the lower areas, perhaps reducing neural refractoriness (time needed to generate a new spike) and enhancing the perceptual salience of attended stimuli (Martinez *et al.* 2001). Vidyasagar (1999) has proposed further that magnocellular/dorsal stream pathways with their rapid transmission and spatial coding properties may provide feedback to earlier stages of the visual cortical pathways (including V1) to selectively facilitate sequential processing at attended locations before they are processed further in the ventral stream. It is by this process that attention would facilitate encoding the letters in the word amongst the sea of words on a page.

Neural activity in primary visual cortex can also be modulated by contextual influences from stimulus contours outside the classical receptive field. The improved discrimination resulting from patterns beyond the classical receptive field was first discovered in MT (Allman *et al.* 1985), which has feedforward and feedback pathways to layers 4b and 6 in cortical area V1 (Maunsell & Van Essen, 1983). Moreover, the background frame of reference influences the tuning of the motion-sensitive neurons in MT (Schlack *et al.* 2007). It is likely that direction-discrimination training modifies the V1-MT feedforward and feedback pathways by tuning up the inhibitory and excitatory connections between magnocellular and linked parvocellular neurons. Since this task is designed using patterns optimal for magnocellular neurons, which predominate in the dorsal pathway, it suggests that the dorsal processing stream provides the attention gateway, as proposed previously (Vidyasagar, 1999, 2001).

The patterns used to train direction discrimination in the current study were designed to train the center of the working range for direction discrimination at both low levels (cortical area V1) and high levels (cortical area MT) of visual processing (Lawton, 1989; Lawton, 2000, 2004, 2007). A 4-octave range of backgrounds centered around each test frequency, would 1) train the directionally selective neurons beyond their classical receptive fields (Allman, Miezen, & McGuiness*,* 1985), and 2) be required to measure the effects of divisive inhibitory surrounds (Foley, 1994) on contrast discrimination.

It has been suggested that the enhanced firing of V1 cells produced by such contours may reflect the grouping together of figural elements and segregation of figure from ground (Hupe *et al.* 1998; Ito & Gilbert, 1999; Lamme & Spekreijse, 2000). Such contextual effects may be mediated both by long-range horizontal connections within V1 and by feedback projections to V1 from higher-tier visual areas, such as MT. It has been proposed that spatial attention may exert a top-down feedback influence on this V1 circuitry for figure-ground enhancement such that attended figures or objects become more perceptually salient (Roelfsema *et al.*, 1998; Ito & Gilbert, 1999; Lamme & Spekreijse, 2000). This saliency could explain why, when multifrequency backgrounds were used for training, thereby activating a wider range of channels tuned to different spatial frequencies, reading speeds increased 4 fold (Lawton, 2007) instead of 2 fold as found in the current study when only sinewave backgrounds were used.

There is some controversy about whether a magnocellular deficit underlies the reading deficits of those with dyslexia. Contrary to the magnocellular deficit theory, recent work (Sperling *et al*. 2005, 2006), suggest that dyslexic readers may suffer from a general inability to adapt their perceptual filters optimally so as to pass signal and exclude noise. These studies present evidence that dyslexic readers are relatively impaired compared to normal readers across a range of detection/discrimination tasks, provided the target is embedded in external noise, but not if the noise is absent. In this connection, it should be noted that all of the test and training stimuli used in the current study's direction-discrimination training were devoid of external noise. Thus, in particular, the finding that the pre-training contrast thresholds for discriminating the direction of motion were significantly higher for dyslexic than for normal readers argues against the noise-exclusion-deficit theory of Sperling *et al*. (2005, 2006).

Presenting backgrounds composed of multiple, harmonically-related spatial frequencies reduces the background noise, enabling an observer to discriminate the direction of motion at low contrasts over a much wider range of spatial frequencies than found when the backgrounds are composed of single sinewave patterns (Lawton, 1985, 1989). Moreover, when background noise was reduced by also using multifrequency backgrounds instead of only sinewave backgrounds in the direction-discrimination training regimen (Lawton, 2007), not only was there a four-fold difference between the initial CSF of dyslexic and normal readers, instead of the two-fold difference found in the current study, but also: 1) the contrast sensitivity for direction discrimination improved significantly more (14-fold instead of 5-fold); and 2) the reading rates improved an average of four-fold instead of two-fold. These results suggest that activating a wider range of spatial frequency channels, as ensues from using multifrequency backgrounds, provides a more robust and salient frame of reference (Lawton, 1985, 1989). Our working hypothesis in this regard is that a more structured background frame of reference improves the dyslexic reader's ability to discriminate the direction of movement by improving figure-ground discrimination for a wider range of patterns, thereby widening the attention gateway (Lawton, 2007).

Other studies that attempt to refute the contribution of magnocellular deficits to the mechanisms underlying dyslexia (Williams *et al*. 2003; Skottun, 2000; Sperling *et al.* 2003) rely upon data using either flicker detection or discrimination to diagnose dyslexia. Neither sensitivity to flicker (counter-phase gratings) nor short duration patterns, as used in flicker discrimination, are optimal stimuli for activating direction-selective cells (DeValois *et al*. 2000; Baker, 1988; Pasternak, 1987). While flickering stimuli are detected in the retina, direction selectivity is not detected until the cortex (Zeki, 1974). At higher levels in the motion pathways, such as cortical area MT, most cells are direction selective (Albright, 1984; Van Essen *et al*. 1981). Furthermore, counter-phase gratings, flickering patterns, required twice as much contrast to detect motion (Pasternak, 1987; Levinson & Sekuler, 1975), compared to sinewave gratings that moved in one direction. Direction discrimination, not flicker discrimination, is the key dependent variable that must be measured both to detect and remediate reading deficits.

Again, it is the *timing* between magnocellular and parvocellular activations that underlies the reading deficits in dyslexia, which can be remediated by a short amount of direction-discrimination training using patterns that optimally activate magnocellular neurons. Moreover, when direction discrimination is done relative to a textured background instead of a uniform field, then the claims in earlier reports that only dysphonetic dyslexics showed magnocellular deficits (Borsting *et al.* 1996; Talcott *et. al.* 2000; Slaghuis & Ryan, 1999, 2006), are refuted by the finding (Ridder *et al.* 2001; Lawton, 2000, 2004, 2007, 2008) that all types of dyslexics have a direction discrimination deficit (putatively conveyed by magnocellular neurons). When patterns that maximally activate directionally selective motion pathways, located in cortical areas V1 and MT, where the background frame of reference influences the tuning of the motion-sensitive neurons (Schlack *et al.* 2007), are used in a direction discrimination task, all types of dyslexics are not only detected, but their reading skills are rapidly improved (Lawton, 2004, 2007, 2008). If magnocellular deficits do not underlie the reading deficits of dyslexics, it is not clear why direction-discrimination training is the only type of training found to enable all types of dyslexics to improve in reading fluency.

Future research will focus on the cortical mechanisms underlying the remarkable improvement in reading fluency associated with direction-discrimination training. Although the current study assumed that direction-discrimination training increases the ratio of signal to internal noise, improving the timing and strength of magnocellular activity in one or more neural populations in the dorsal pathway, the current study does not permit strong conclusions about the neural locus of the crucial learning. If the relevant neural population is in the LGN, then (because these neurons are not selective for motion direction) the training should be equally effective if the motion-discrimination task is replaced by a flicker-detection task. Other likely neural loci are striate cortex (V1) and MT. If the crucial site is MT, then the training should be equally effective if the sinusoids used in the motion-discrimination task are replaced by broadband stimuli such as moving fields of dots, which drive MT cells very strongly (Albright, 1984; Newsome & Pare, 1988; Zohary *et al.* 1994). Finally, if it is the motion-selective neurons in striate cortex that are crucial, then (because these neurons are both spatial frequency-selective and direction-selective) one might reasonably expect that neither the flicker-detection stimuli nor broadband motion stimuli would work very well as training stimuli. Future studies will address these issues.

Conclusions

Dyslexics can be differentiated from normal readers by their significantly lower sensitivity to the direction of movement. A simple computer-based direction-discrimination training regimen has been shown to provide significant, rapid, and permanent increases, in both the direction discrimination sensitivity and in the reading fluency of dyslexic readers. Finally, data from the current study support the view that dyslexia is caused by magnocellular timing deficits in the dorsal stream.

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PDI has developed and is marketing the PATH to Reading program (www.pathtoreading.com) based on the clinical techniques described in this paper. It is available worldwide for vision and educational therapists from PDI, and for schools from Early Childhood Parenting Institute, a nonprofit, tax-exempt corporation.

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List of Figures

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

Figures 2a-d. Mean Contrast Sensitivity after first (dotted lines), second (dashed lines), and fifteenth (solid lines) replications, and standard errors of the mean for Dyslexic and Normal Readers when discriminating the direction a 0.25 cyc/deg test pattern (Fig. 2a), a 0.5 cyc/deg test pattern (Fig. 2b), a 1 cyc/deg test pattern (Fig. 2c), a 2 cyc/deg test pattern (Fig. 2d), moved relative to each of the 5 backgrounds, where f is the spatial frequency of the test pattern.

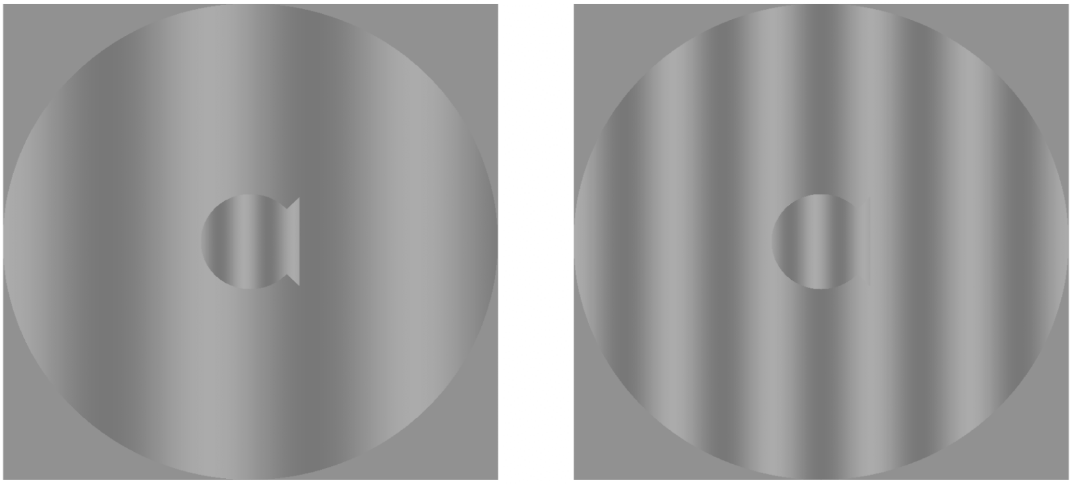
Figure 3. Mean Contrast Sensitivity for each test frequency, when averaged across the five background frequencies for Dyslexics, Fig. 3a, and Normal Readers, Fig. 3b, and standard errors of the mean.

Figure 4. Initial and Final Reading Speeds for 3 Training Regimens for Children with Dyslexia and Normal Readers.

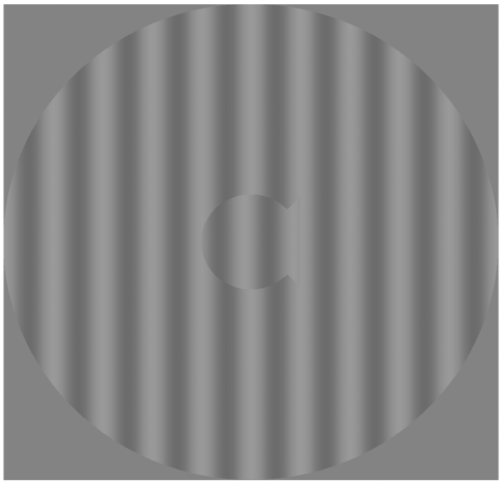
Figure 5. Estimated final reading speeds for the 3 training regimens for Dyslexics (dashed line) and Normal Readers (solid line). In addition to Reading Skill Level (dyslexic vs. normal readers) and Training Regimen (no training, word-training, and direction-discrimination training), the model used to derive the plotted estimates also included a covariate. For each child, the covariate was the difference between that child's initial reading fluency and the mean initial reading fluency of their Reading-skill cohort. Error bars give 95% confidence intervals. The straight dashed and solid lines give the mean reading speeds prior to training of the dyslexic and normal readers, respectively.

Figure 6. Reading Skills for 6 dyslexics who were trained in direction discrimination twice a week for 15 weeks in 2002-2003 and 15 weeks in 2003-2004.

Test = 0.5 cpd



Background = 0.125 cpd **Background = 0.25 cpd**



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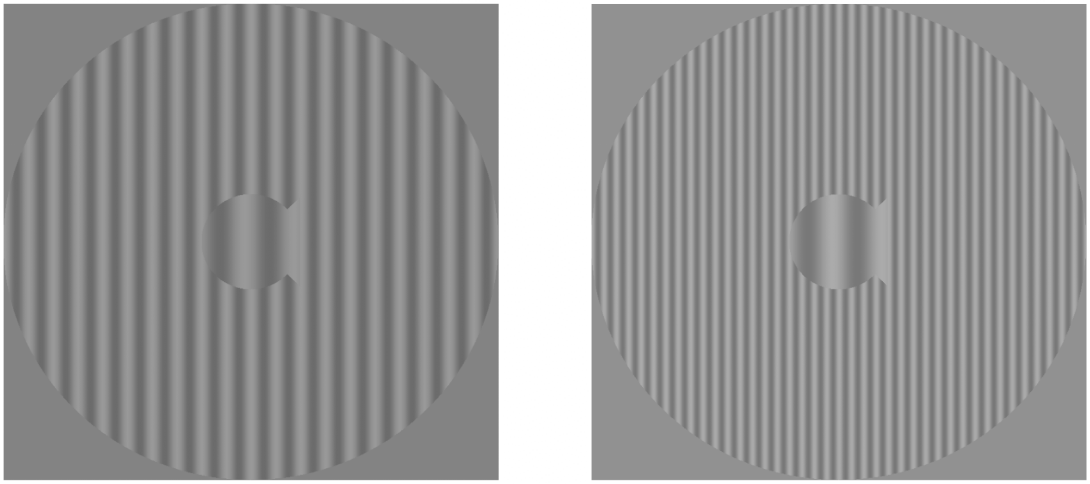


Background = 1 cpd **Background = 2 cpd**

Fig. 1. Sample patterns for test frequency = 0.5 cyc/deg (cpd) on Different Backgrounds

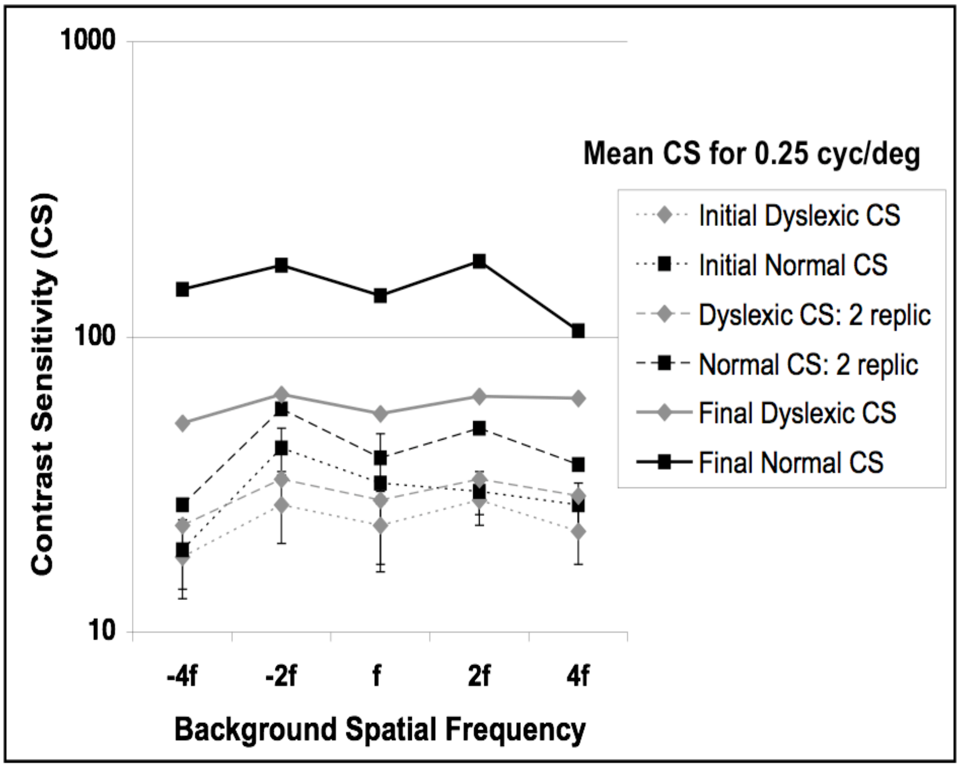


Figure 2a.

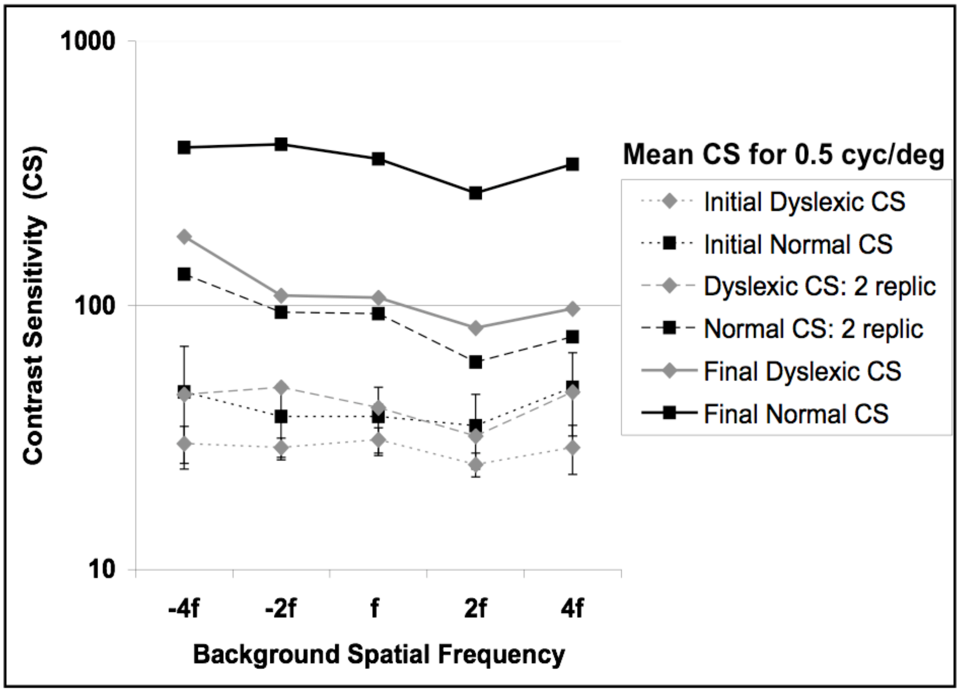


Figure 2b.

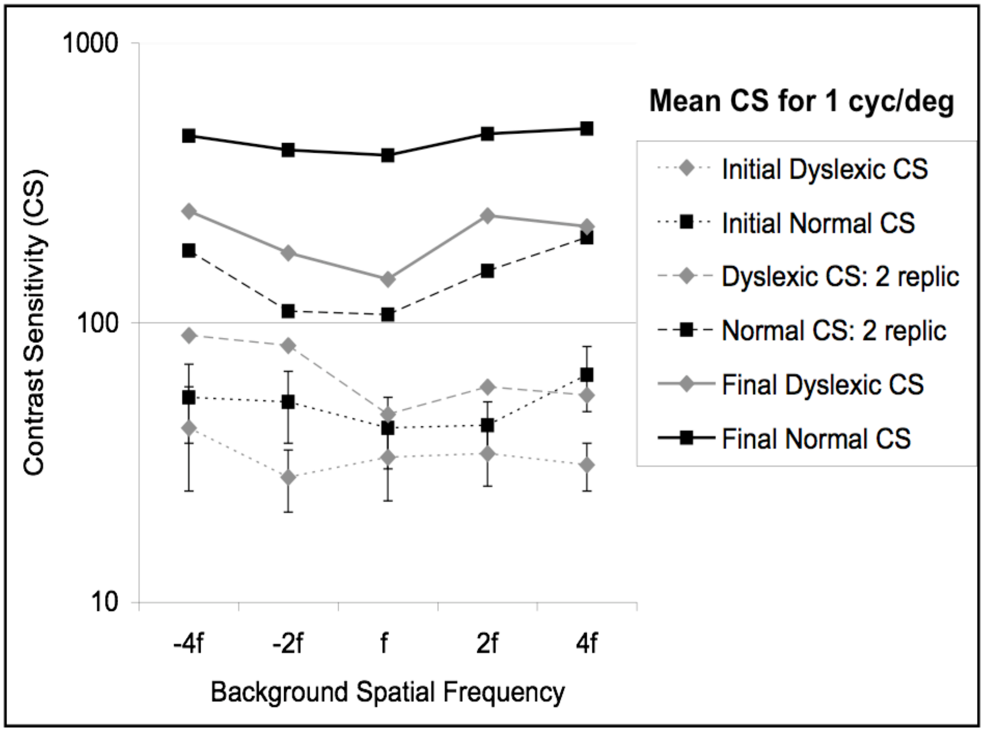


Figure 2c.

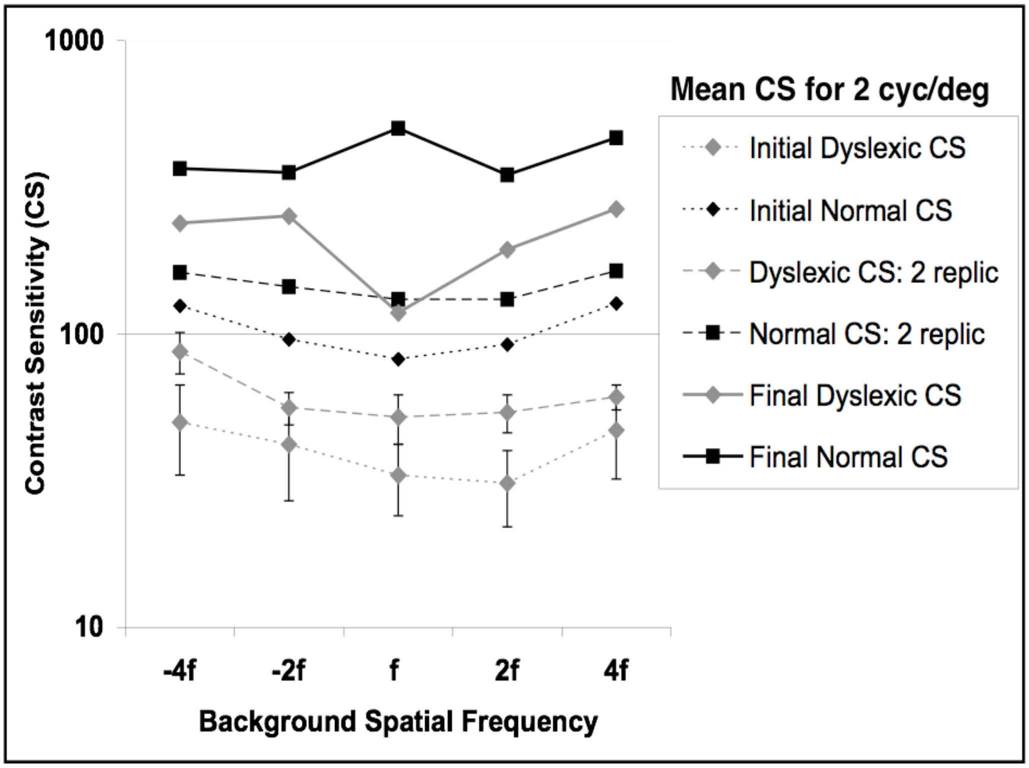


Figure 2d

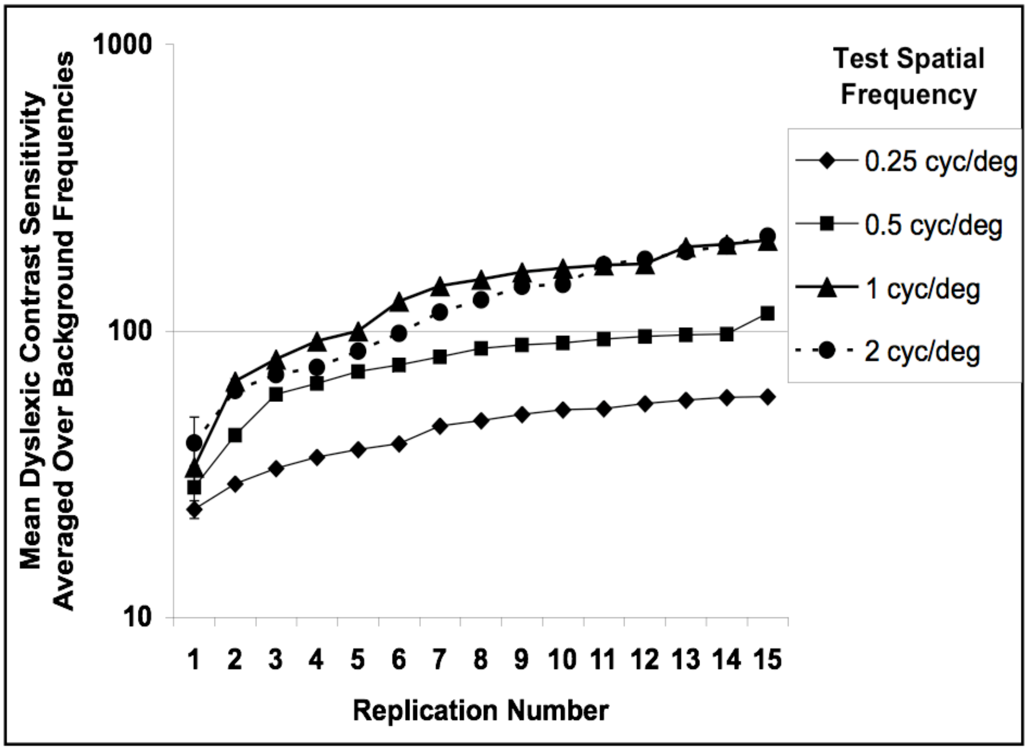


Figure 3a.

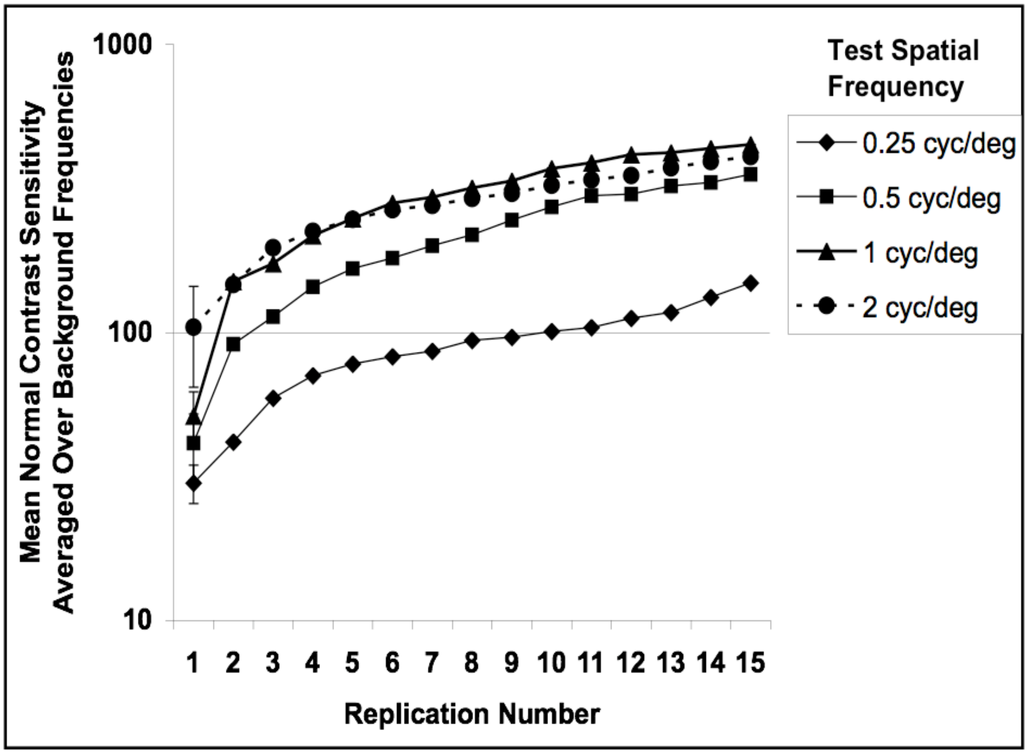
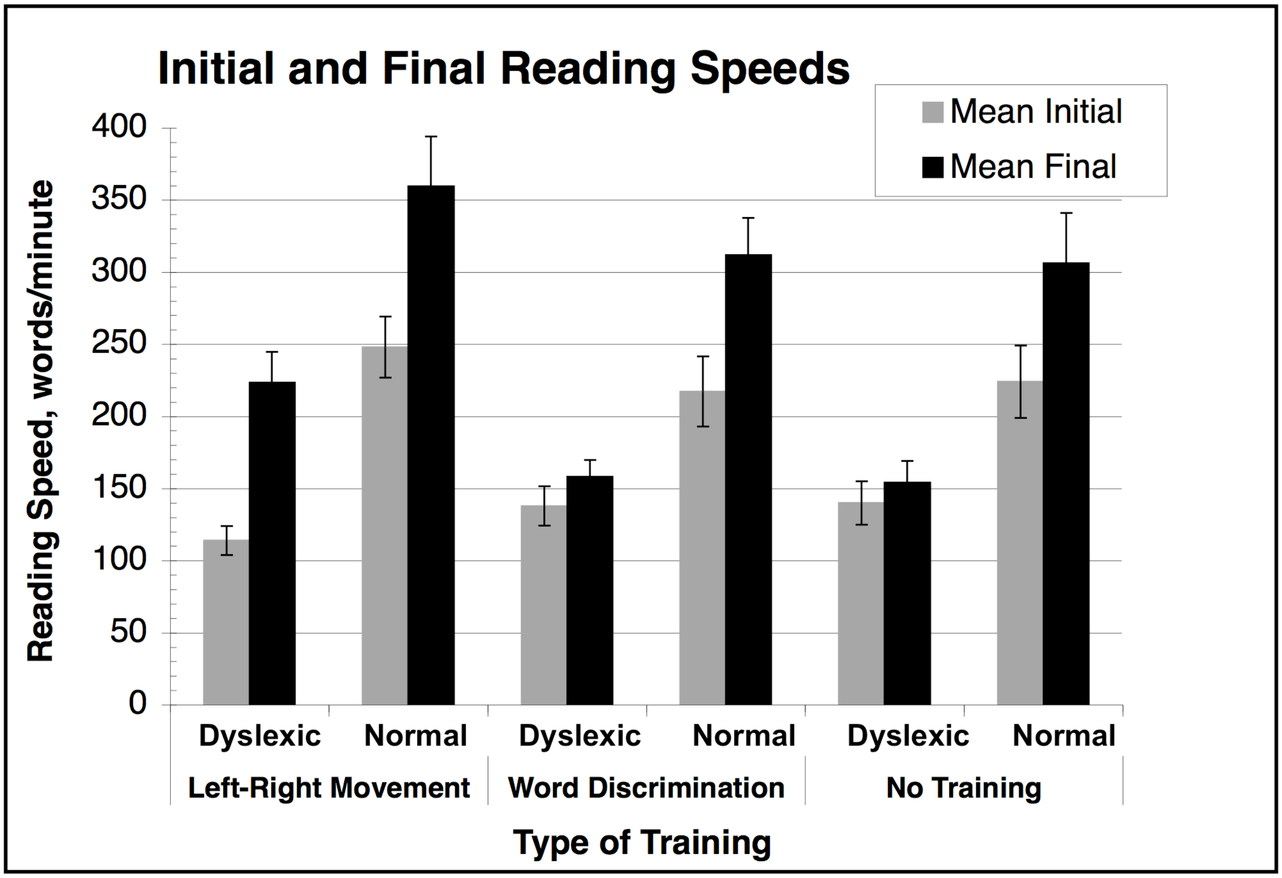


Figure 3b.



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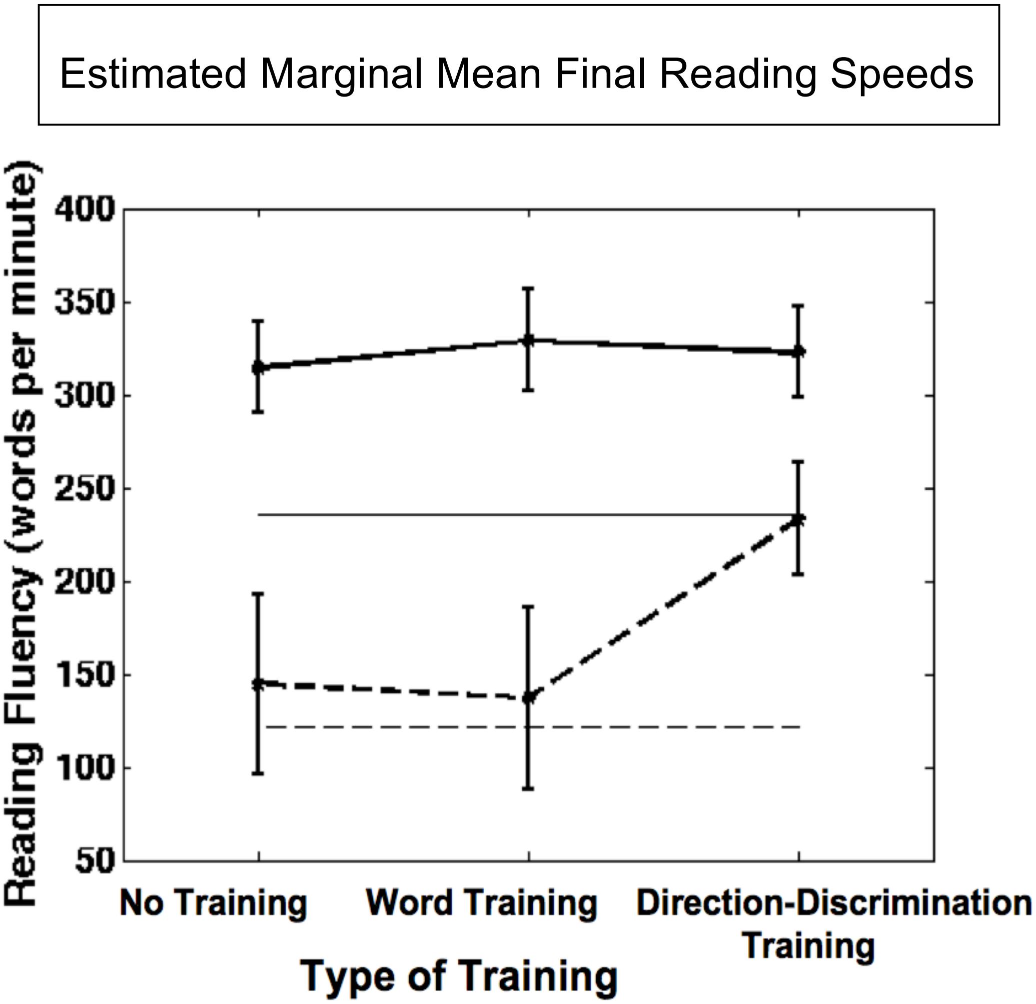

Figure 5. Estimated final reading speeds for the 3 training regimens for dyslexics (dashed line) and normal readers (solid line). In addition to Reading Skill Level (dyslexic vs. normal reader) and Training Regimen (no training, word-training, and direction-discrimination), the model used to derive the plotted estimates also included a covariate. For each child, the covariate was the difference between that child's initial reading fluency and the mean initial reading fluency of their Reading-skill cohort. Error bars give 95% confidence intervals. The straight dashed and solid lines give the mean reading speeds prior to training of the dyslexic and normal readers, respectively.

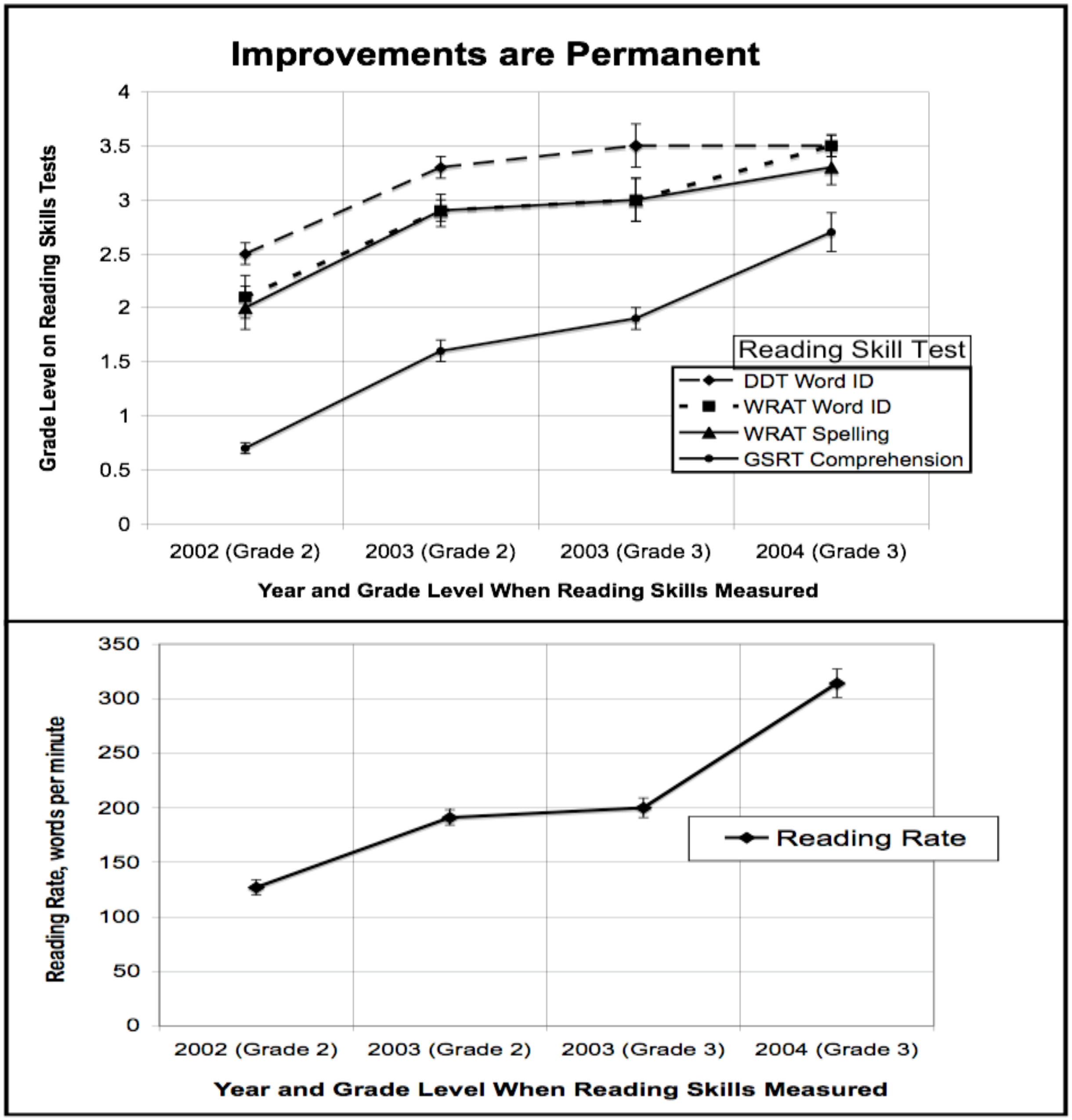

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Table 1. Initial Equivalent Grade Level or Reading Speed on Literacy Tests and Significance Levels on Single Factor Analysis of Variance Test *t*-tests, all with 105 degrees of freedom .

Type of Literacy Test	Initial Grade Level for Dyslexics	Initial Grade Level for Normals	*t*-test Value	Significance Level for Dyslexic-Normal Difference
DDT Reading GL	2.9±0.2	5.4±0.3	7.5	$p < 0.001$
WRAT Reading GL	2.9±0.1	3.9±0.2	3.4	$p < 0.001$
WRAT Spelling GL	2.1±0.1	3.1±0.1	4.8	$p < 0.001$
GSRT Comprehension GL	0.8±0.1	1.5±0.1	4.7	$p < 0.001$
WJ Word Attack	3.4±0.4	6.4±0.5	4.4	$p < 0.001$
CTOPP Rapid Digit Naming	2.6±0.2	3.5±0.2	2.7	$p < 0.004$
CTOPP Rapid Letter Naming	2.6±0.2	3.6±0.2	4.1	$p < 0.001$
CTOPP Rapid Color Naming	1.4±0.3	2.1±0.2	2.1	$p < 0.02$
CTOPP Rapid Object Naming	1.9±0.3	2.5±0.2	2.0	$p < 0.03$
LAC	2.7±0.2	4.2±0.2	4.2	$p < 0.001$
Reading Speed	121 words / min. ± 7	235 words / min. ± 13	7.1	$p < 0.001$

Table 2. Significance levels for *t*-tests, having 30 degrees of freedom**,** comparing improvements in reading skills tests for dyslexic students in the direction-discrimination training versus pooled control groups

(* indicates significance at Bonferroni corrected level of 0.0125).

Type of Literacy Test	t-test Value	Significance Level
DDT Reading Grade Level	3.25	$p < 0.001$*
WRAT-3 Reading Test	2.53	$p < 0.009$*
WRAT-3 Spelling Test	2.85	$p < 0.004$*
GSRT Reading Comprehension	3.34	$p < 0.001$*
WJ Word Attack	1.38	$p < 0.09$
CTOPP Rapid Digit Naming	1.06	$p < 0.1$
CTOPP Rapid Letter Naming	0.30	$p < 0.3$
CTOPP Rapid Color Naming	1.24	$p < 0.1$
CTOPP Rapid Object Naming	0.86	$p < 0.2$
LAC	0.69	$p < 0.2$

Table 3. Average improvement [either speed (words/minute) or Grade Level (GL)] on the reading skill tests that improved significantly for dyslexics who received **direction-discrimination training**, compared to dyslexics in the control groups: the word training and no training groups, in that order.

Reading Skills Test	**Initial Speed**	**Final Speed**	**Mean Improvement**	**95% Confidence Intervals**
Computer Reading Speed (words/minute)	**114**	**223**	**110**	**81 to 138**
	138	158	20	8 to 33
	123	147	24	7 to 40
Reading Skills Test	**Initial GL**	**Final GL**	**Mean Improvement**	**95% CI**
DDT Reading	**2.8**	**4.1**	**1.3**	**0.7 to 1.8**
	3.3	3.4	0.1	-0.8 to 1.8
	2.9	2.9	0.0	-0.9 to 0.9
WRAT-3 Reading	**2.6**	**3.6**	**1.1**	**0.7 to 1.5**
	2.7	3.5	0.7	0.4 to 1.0
	2.8	2.9	0.1	-0.3 to 0.5
WRAT-3 Spelling	**2.0**	**3.3**	**1.2**	**0.8 to 1.5**
	2.1	2.7	0.6	-0.2 to 1.4
	1.8	2.2	0.4	0.2 to 0.6
GSRT Comprehension	**0.8**	**2.0**	**1.2**	**0.7 to 1.6**
	0.7	1.0	0.2	-0.3 to 0.8
	0.8	1.4	0.5	-0.1 to 1.1