Filtered Text and Direction Discrimination Training Improved Reading Fluency for Both Dyslexic and Normal Readers

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Abstract

Background: Over 67% of children in 4th grade are reading below grade level, which means they are twice as likely to drop out of school. Previous research has found that children who are slow readers have reduced contrast sensitivity for detecting the direction of movement, and that improving their movement contrast sensitivity by training with sinusoidal gratings moving relative to fixed background gratings significantly increases their reading fluency. Since observers having reduced contrast sensitivity show much faster reading speeds when text is sharpened with digital filters, it is likely that children will also read filtered text more quickly than unfiltered text.

Methods: Orientation discrimination contrast thresholds were measured for both dyslexic and normal readers in grades kindergarten through third grade and used to construct individualized digital image enhancement filters. Computer-based reading speeds were measured for both unfiltered and filtered grayscale text before and after training on direction discrimination. Following training, reading speeds for both unfiltered and filtered equiluminant colored text were measured as well.

Results: Reading rates were twice as fast when utilizing filtered text to compensate for losses in orientation discrimination contrast sensitivity compared to unfiltered text, both before and after direction discrimination training. Both filtered and unfiltered colored text was read at least 30% more slowly than filtered or unfiltered equiluminant grayscale text. The effects of training on direction discrimination were also significant for both dyslexic and normal readers ($p < 0.008$), doubling reading rates for both dyslexics and normal readers. Following training on direction discrimination, contrast sensitivity functions improved an average of four-fold for normal readers and five-fold for dyslexics, showing rapid perceptual learning in children aged 5 to 8 years.

Conclusions: Finding much faster reading speeds for filtered text shows the value of individualized contrast enhancement to improve reading skills. These image enhancement filters are unique and work well to improve the reading performance of children with contrast sensitivity losses. Moreover, training on direction discrimination improved the reading fluency of both dyslexic and normal readers. Furthermore, the fact that colored text was always read much more slowly than equiluminant grayscale text may also suggest that the colored backgrounds produced by the Irlen lenses do not improve reading fluency. Finally, both digital image enhancement and direction discrimination training provide effective, convenient, and relatively inexpensive tools to improve reading.

Key Words: contrast sensitivity, magnocellular, motion discrimination, orientation discrimination, dyslexia, image enhancement, colored filters, reading fluency

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Correspondence regarding this article can be e-mailed to tlawton@pathtoreading.com or sent to Dr. Teri Lawton, PhD, Perception Dynamics Institute, 253 Sea Forest Court, Del Mar, CA 92014 or by phone at 310-903-6009. All statements are the author's personal opinion and may not reflect the opinions of the College of Optometrists in Vision Development, Optometry & Vision Development or any institution or organization to which the author may be affiliated. Permission to use reprints of this article must be obtained from the editor. Copyright 2008 College of Optometrists in Vision Development. OVD is indexed in the Directory of Open Access Journals. Online access is available at http://www.covd.org. In the interest of full disclosure, Dr. Lawton does have a financial interest in the product and/or services describe within this article.

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Introduction

More than half of the nation's elementary, middle, and high school students are reading below grade level. Students reading below grade level cannot master complex concepts easily and are twice as likely to drop out of school. Reading depends on having appropriate visual function, which can be improved significantly by training on discriminating the direction of movement of sinusoidal gratings relative to fixed background gratings.[1-4]

Compared to adults, children have significantly reduced contrast sensitivity for discriminating the direction of motion as measured by determining the direction that sinusoidal gratings of various spatial frequencies move relative to fixed background gratings.[1] In addition, previous studies have found dyslexics to be significantly less sensitive than normal readers when discriminating the direction of motion.[1-6] Besides a level difference in sensitivity to direction discrimination, the shape of the Contrast Sensitivity Function (CSF) of normal readers is noticeably different from that of dyslexic readers: A normal efficient reader's CSF is concave downward, while that of a dyslexic reader is convex upward. This shape difference arises because direction discrimination is easy for normal readers, and difficult for dyslexic readers, when test and background frequencies are equal. When test and background frequencies are equal, then both patterns are processed by the same spatial frequency channel, requiring figure-ground discrimination to complete the direction discrimination task. The CSF shape difference between dyslexic and normal readers further indicates that normal readers have learned figure-ground discrimination, whereas those with dyslexia find figure-ground discrimination to be very difficult. Since motion coherence thresholds using random dot patterns only reveal an overlapping level difference,[5,7] sinewave gratings provide a more effective stimulus for detecting different levels of reading dysfunction than do random dots.

Image enhancement filters which sharpen images for people with reduced contrast sensitivity have been shown to increase reading fluency significantly.[8]

The Contrast Sensitivity Function (CSF) for orientation discrimination measures an observer's sensitivity to higher spatial frequencies than the CSF used to measure motion discrimination. This is due to the fact that motion discrimination requires lower spatial frequencies than needed for pattern discrimination.[9] Since these higher spatial frequencies are essential for discriminating text, this study measures a child's orientation discrimination CSF, which has been used previously to create individualized image enhancement filters to improve reading fluency.[8] Since training in a direction discrimination task has been shown to increase the speed of reading *unfiltered* text significantly in children,[1-4] this study determines whether training on direction discrimination also increases the reading speed for *filtered* text in children 6 to 8 years old.

It is conjectured that this training regimen significantly increases the effectiveness of the magnocellular pathways in mediating reading, as suggested by controlled-validation studies.[1-4] Since the magnocellular pathways are relatively insensitive to color variations,[10] colored filters like the Irlen lenses[11] should not improve reading fluency. Therefore, the reading speed for both unfiltered and filtered white text on a black background is compared with the reading speed for both unfiltered and filtered equiluminant colored text on a black background. The effects of five variables on reading fluency were examined. They were: 1) text color 2) unfiltered vs. filtered text, 3) before vs. after training on direction discrimination, 4) normal vs. dyslexic subjects, and 5) age.

Methods

Participants

This study included 30 children in grades 1-3, ages 6-8. Five readers who were dyslexic and 5 who were efficient readers were included at each grade level. Five children in Kindergarten (2 girls and 3 boys), and 2 adults aged 42 years (1 man and 1 woman) were also studied. These groups were included for data bracketing purposes. There were two comparison groups studied: normal efficient readers and dyslexic readers. The Dyslexia Screener (TDS), a rapid 5 minute test,[12] was used to classify children into categories of either nondyslexia or different degrees of dyslexia in terms of the 3 major subtypes: dysphonetic (problems with word-attack coding, being more 'auditory'), dyseidetic (problems with whole-word coding, being more 'visual'), or mixed (both dyseidetic and dysphonetic), as originally specified by Boder.[13] The high predictive power of the TDS (87%) for identifying poor readers, who are dyslexic, has been validated using the Woodcock-Johnson standardized reading tests.[14]

Of the 15 children in grades 1-3 who were classified as dyslexic, 6 were dysphonetic, 4 were dyseidetic, and 5 were mixed ranging in severity from borderline markedly below normal. Most dyslexics (25) were at grade level for decoding reading. Approximately half of the children were girls (17) and half were boys (13).

To be included in this study, subjects had to have 20/20 visual acuity, normal intelligence as verified by standardized tests administered by the school, and no known visual abnormalities, or obvious behavioral or neurological disorders. All vision exclusion information was provided by the school nurse, who screened each child's vision. This study had IRB and school district approval, and satisfied the Helsinki declaration.

Apparatus

A Sun IPC SPARCstation was used to present the stimulus patterns and record the observer's responses. The Sun SPARCstation display, made by Sony, had a high resolution of 1160x900 pixels, each pixel having 256 intensity levels for the red, green, and blue guns. This high-resolution display ensured that the filtered text varied smoothly and was not pixilated. Mean display luminance was calibrated and set to 67 cd/m^2 at the beginning of this study. The mean luminance was held constant during each session, including the interval between pattern presentations, to ensure that the gain of the contrast response function remained constant during testing. At the end of this study, a mean luminance of 8 cd/m^2 was also used to enable presenting all colored text with equal luminance at high contrast. All text, either white or colored, was presented on a black background. All reading rates in figures showing both colored and achromatic text (Fig. 5) were done using a mean luminance of 8 cd/m^2.

Procedures

Data were collected during the school day at a local public school and occurred at most once a week each morning between 8-12 noon, in a room devoted solely to this task. All measurements of contrast sensitivity and reading rates were done on an individual basis in 10-15 minute sessions by the author, who was also the investigator.

Tasks

Orientation Contrast Sensitivity Function (CSF) Measurements

The sinewave gratings used to measure a student's CSF comprised a single spatial frequency component that varied over 5 octaves, from 0.125 to 8 cyc/deg, in 1-octave steps up to 2 cyc/deg, and half-octave steps above that. The sinewave grating appeared within a circular 600 pixel wide aperture that spanned 7.5 deg at a viewing distance of 57 cm. The student's task was to push a key indicating whether the grating, which was displayed for 500 msec, was vertical (up-down) or horizontal (sideways) in its orientation. Auditory feedback was given after each pattern to indicate whether the observer chose the orientation of the pattern correctly. A spatial 2 Alternative Forced-Choice (AFC) staircase procedure[15] was used for the interactive measurement of each student's contrast threshold function for orientation discrimination.

Following a short practice session that set the initial contrast of the sinewave grating, the test run was initiated. At the beginning of the test run, the contrast of the grating was decreased one step of 0.5%, each time the student correctly identified the orientation. Following the first incorrect response, the staircase procedure was used. In the staircase, the student had to correctly identify the orientation of the sinewave grating three times in a row before the contrast was decreased one step. The contrast was increased one step each time the orientation of the grating was identified incorrectly. Each contrast threshold for orientation discrimination consisted of approximately 20-30 trials. This task took one session to test each student across all 8 spatial frequencies. Two to three contrast thresholds for each spatial frequency, each replication measured one week apart, were used to determine the mean and standard deviations of the graphed contrast thresholds.

Reading Rate Measurements

Reading fluency was assessed by how rapidly a child was able to read aloud. The computer-based reading rate task[16] flashed 5 words of continuous text for different durations from an interesting, easy-to-read poem. To ensure that at least two saccades were required to read each line, the lines from the poem were edited so that each line consisted of five words of text. To ensure that the text could not be memorized, the poem was extended from 80 lines to 230 lines of text, with the help of the school's reading specialist, so that the child always read novel text during the reading rate task.

Large (0.5 cm wide by 0.5 to 0.75 cm high) *sans-serif* letters, either white or colored, were presented on a black background to test reading rates. This size letter enabled text to be read easily at a distance of 57 cm from the screen. A sans-serif font with rounded edges was chosen because this font was not ornate, has no jagged or protruding edges, and presumably being easy to read. The child could read the five words of text as it was being presented or when the presentation was finished. Therefore, the reading rate was not limited by the child's rate of speaking. The investigator chose a rate of text presentation that was continuous and comfortable for the child. Initially the speed of presentation was increased from 10 words/min until four out of five words were not read correctly and in the correct order. At the first incorrect response, another two alternative forced-choice (2AFC) double staircase procedure was implemented, decreasing the speed by 1 step (12%) each time the text was not correctly identified, and increasing the speed by 1 step only when the child correctly read subsequent lines of text three times in a row. The mean reading-speed threshold was computed from two threshold measurements, each consisting of approximately 20-30 trials. This task took between 5-10 minutes.

The relative improvement in reading speed was determined by dividing the final reading speed by the initial reading speed, so that the initial reading speed was used to normalize the amount of improvement. Reading speeds for filtered test were measured before the reading speeds for unfiltered text and white test before colored text, to ensure practice was not a factor in reading filtered or achromatic test more rapidly, as found previously.[8]

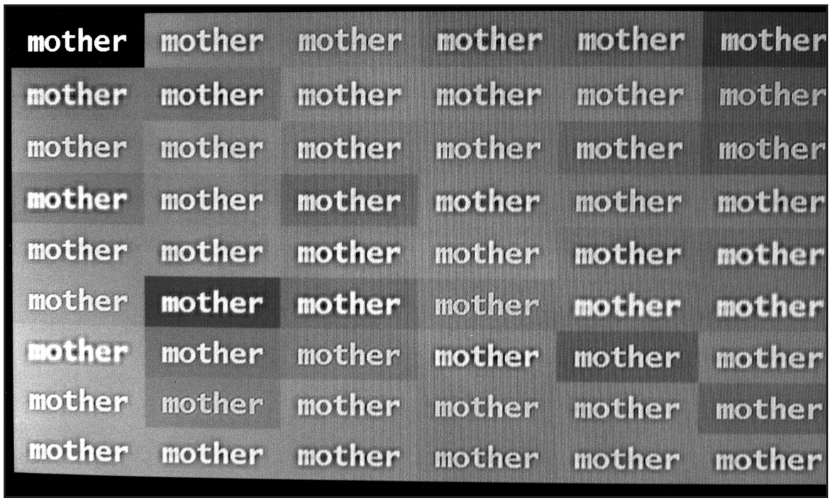

Figure 1: *Unfiltered and Filtered words for different children in this study.*

Image Enhancement Filter Design

The image enhancement transfer function is designed to enhance noisy images that have been degraded by a known optical transfer function[15] by boosting the less visible spatial frequency components relative to the sensitivity of a normal adult observer. The orientation discrimination contrast sensitivity function was used to determine the normalized contrast sensitivity function (NCSF) = (Child's CSF / Adult's CSF), the optical transfer function that is used in the image enhancement filters.[7] The background varies from black to gray to make room for the dark outline the filter places around each letter, as seen in Fig. 1. The algorithms used to derive the image enhancement filters have been described previously.[7]

Filtered Words

Words were first magnified and then filtered, since reading performance for observers with contrast sensitivity loss is based on retinal-based angular frequencies, and not object-based spatial frequencies.[18] Words were filtered as a unit, and the filtered words, having a border equal to one letter width, were strung together as text. There were often borders between the filtered word images, due to the scaling mentioned above. All children reported, however, that these borders were blurred and did not help segment the text string into words. The space between each word was the more salient cue used to segment the text string.

Samples of filtered and unfiltered text for each of the students are shown in Fig. 1. The individualized image enhancement filters, causing white text on a black background to be displayed in shades of gray, are matched to each student's NCSF. Filtered text for each student had different amounts of enhancement across the range of spatial frequencies tested, seen as differences in the amount and extent of dark ringing around each letter.

Direction Discrimination Training (PATH to Reading therapy)

Following initial reading rate measurements at high luminance using both filtered and unfiltered text, each child was trained on direction discrimination, training to discriminate the left-right direction of movement of sinusoidal patterns with varying spatial frequencies, for various amounts of time, from 1-6 complete replications of the 20 pattern sequence, completed in several sessions spaced approximately 1 week apart. Most children completed 2 replications over a period of three months. Since the methods for this direction discrimination training have been reported previously,[1-4] they will only be described briefly here.

In a given staircase run, the center spatial frequency, ωtest, is either 0.25, 0.5, 1, or 2 cyc/deg, and the surround grating spatial frequency, ωbackground, is either equal to the test frequency or 1 or 2 octaves higher or lower than the test frequency. A full training cycle, one replication, 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). The mean luminance was maintained at 67 cd/m^2.

The child's task 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, the test and background grating was set to 5% contrast. Each time the child correctly identified the direction the pattern moved, the contrast of the test grating was lowered, until the subject made an incorrect response. Following the first incorrect response, a 2AFC double-staircase procedure[15] 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. Three successive correct responses reduced test grating contrast by one step. This staircase procedure, which took between 10-15 minutes to complete, estimated the contrast needed for 79% correct responses. Following direction discrimination training, reading rates for filtered and unfiltered text were measured.

Results

Orientation discrimination CSFs show developmental lag in children, especially dyslexics

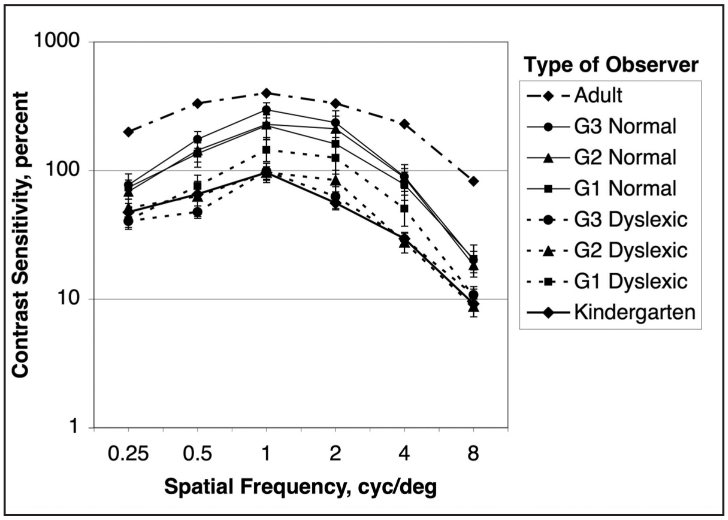

Figure 2: *Orientation Contrast Sensitivity Functions (CSF) for normal and dyslexic children in grades 1-3, bracketed by the CSF of children in Kindergarten and 43 year old adults who were normal readers.*

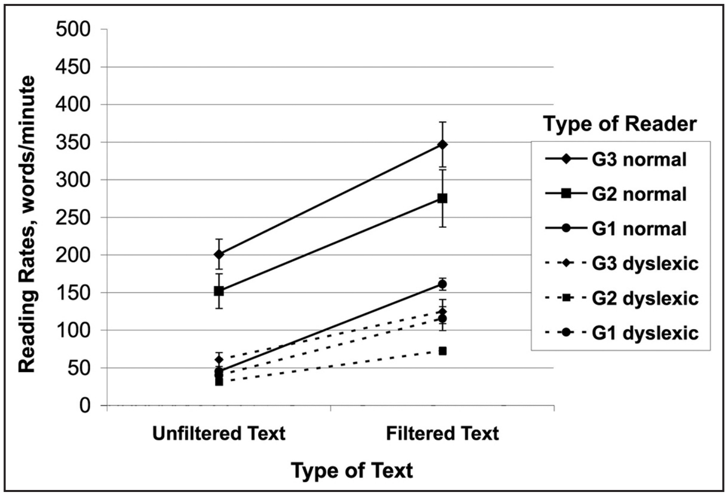

Figure 3a

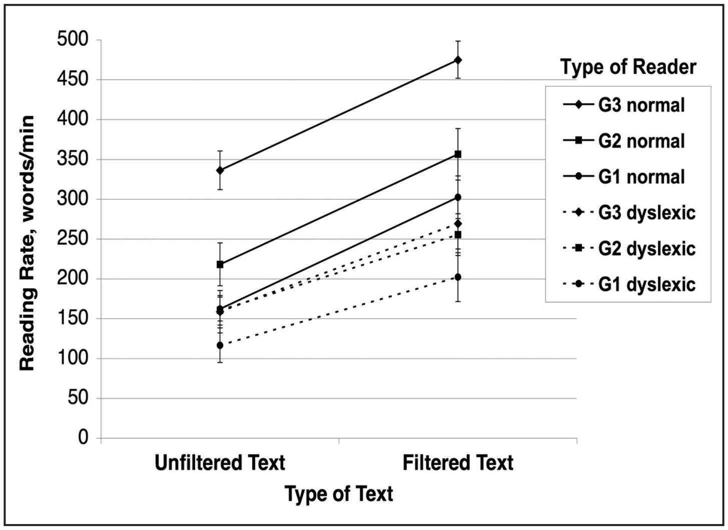

Figure 3b

Figures 3: *Reading rates for unfiltered text and filtered text before (3a) and after (3b) direction discrimination training.*

Table 1. Amount Filtered Text Read Faster than Unfiltered Text Before and After Training on Left-Right Movement Discrimination, ie. (Reading Speed of Filtered Text) / (Reading Speed of Unfiltered Text) and Significance Levels for Normal and Dyslexic Readers

Normal Readers	**Before Training**	**After Training**
Grade 1	3.6***	2.0***
Grade 2	1.7***	1.9***
Grade 3	1.7***	1.8***
Dyslexic Readers	**Before Training**	**After Training**
Grade 1	2.9***	2.1***
Grade 2	2.1***	2.1***
Grade 3	2.1***	1.7***

**** denotes p < 0.001. There were 5 subjects in each group.*

Table 2. Amount Text Read Faster Following Training on Left-Right Movement Discrimination, ie. (Reading Speed of Text Following Training) / (Initial Reading Speed) and Significance Levels for Normal and Dyslexic Readers for Both Unfiltered and Filtered Text presented at a high mean luminance.

Unfiltered Text	**Normal Readers**	**Dyslexic Readers**
Grade 1	3.4***	2.8***
Grade 2	1.5***	2.5***
Grade 3	1.4***	2.6***
Filtered Text	**Normal Readers**	**Dyslexic Readers**
Grade 1	1.9***	2.0***
Grade 2	1.6***	2.4***
Grade 3	1.9***	2.1***

**** denotes p < 0.0001. There were 5 subjects in each group.*

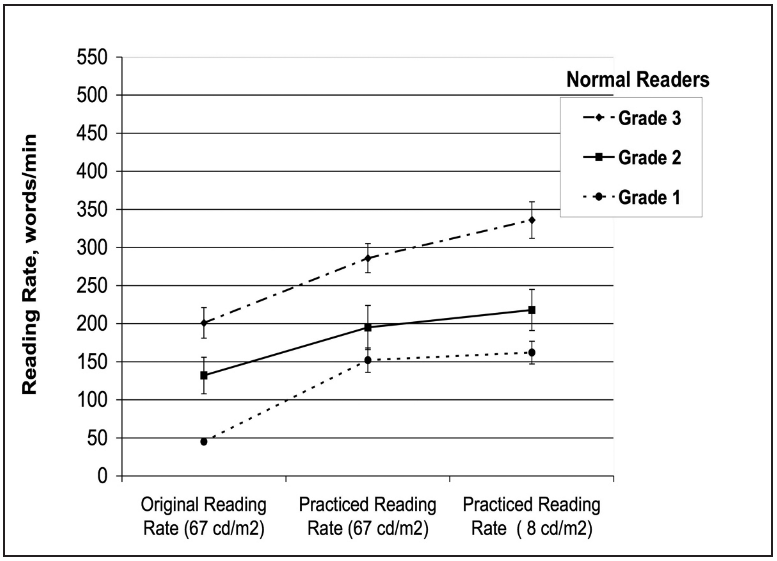

Figure 4a

Each child's orientation discrimination Contrast Sensitivity Function (CSF) was measured to create an individualized image enhancement filter. The orientation discrimination CSFs are shown in Fig. 2. Orientation discrimination CSFs were lowest for children with dyslexia. Their CSFs were lower than the CSFs of age-matched efficient readers, whose CSFs were lower, in turn, than an adult's CSF. These differences are significant, p < 0.001, when analyzed using a t-test for paired sample means. This indicates that dyslexics lag developmentally in their orientation CSF when compared to age-matched normal readers. The CSF for adults and for children in Kindergarten bracketed the CSF of children in grades 1-3, the difference in grade level being significant at p < 0.001, when analyzed using a 2-factor ANOVA for spatial frequency and grade level.

Training on left-right movement discrimination improved reading speed

Filtered text was read twice as fast as unfiltered text both before (Fig. 3a) and after (Fig. 3b) training on direction discrimination (see Table 1). This difference was highly significant when analyzed using paired comparison t-tests for both normal and dyslexic readers (see Table 1). Both dyslexic and normal readers showed a developmental trend: reading speed increased as the child's grade level increased from first to third grade. Moreover, reducing the mean luminance did not reduce the effectiveness of filtered text to improve reading rates, as shown in Figures 4a and 4b.

As the child advanced from first to third grade, reading fluency, measured by the rate of reading simple continuous text, showed a clear developmental trend, see Fig. 3. The rate, *i.e.* the number of words/minute, at which a child could read text increased significantly as the child's age advanced from 6 to 8 years old for both normal readers (Figs. 3a,b), p < 0.001, and for those with dyslexia (Figs. 3a,b, p < 0.001, when analyzed using a 2-factor ANOVA. Moreover, the reading speeds of normal readers were significantly faster than those of dyslexic readers, both before and after training on left-right movement discrimination, $p < 0.01$, when analyzed using a repeated-measures 2-factor ANOVA.

Following a short amount of training on direction discrimination, overall reading speed improved significantly ($p < 0.0001$ for normals and $p < 0.008$ for dyslexics), doubling on average for both dyslexic and normal readers, as shown in Table 2. Reading speeds improved for all types of dyslexics, dyseidetic, dysphonetic, and mixed. These increases in the reading speed of both dyslexic and normal readers following training on direction discrimination were consistent with validated studies.[2-4] Following training on direction discrimination, first and second grade dyslexic children read at the speed that normal first- and second-grade read *before* their training on direction discrimination.

Moreover, reading speeds doubled when the frequency of training increased (Fig. 6), this improvement being highly significant, $p < 0.0001$, when analyzed using a repeated-measures 2-factors ANOVA. Following direction discrimination training, children who completed six replications improved four-fold in reading speed, twice as much as children who completed only two. This increase in reading speed as the frequency of training increased was also found in a controlled validation study.[3]

Direction discrimination CSF differentiates between normal and dyslexic readers

Following training on direction discrimination, both level and shape differences (concave downward for normal readers, as opposed to convex upward for dyslexics) were found between the direction discrimination CSFs for normal and dyslexic readers. (Fig. 7). Normal readers were 3-6 times more sensitive than dyslexic readers to the direction in which vertical sinewave gratings moved (Figures 7, 8), this difference being highly significant, $p < 0.001$, when analyzed using a repeated-measures 2-factors ANOVA, across the 4 test frequencies and 2 types of readers. All types of dyslexics, dyseidetic, dysphonetic, and mixed, had significantly lower CSFs than normal readers.

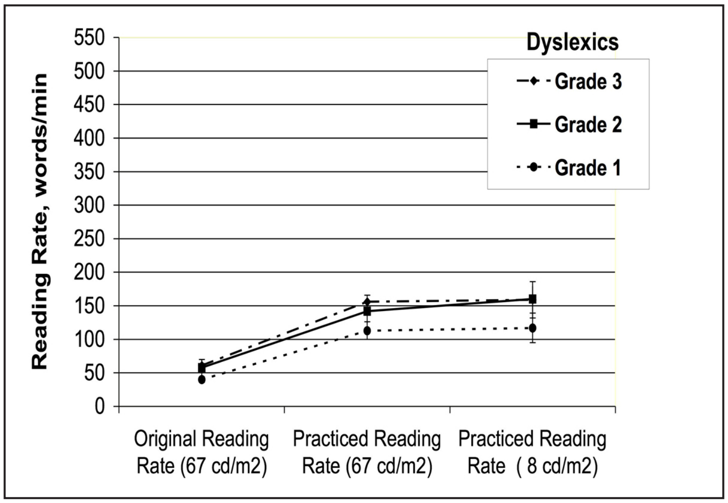

Figure 4b

Figures 4: *Reading rates for unfiltered text before and after direction discrimination training at both high and low mean luminance levels for both normal readers (4a) and dyslexic readers (4b).*

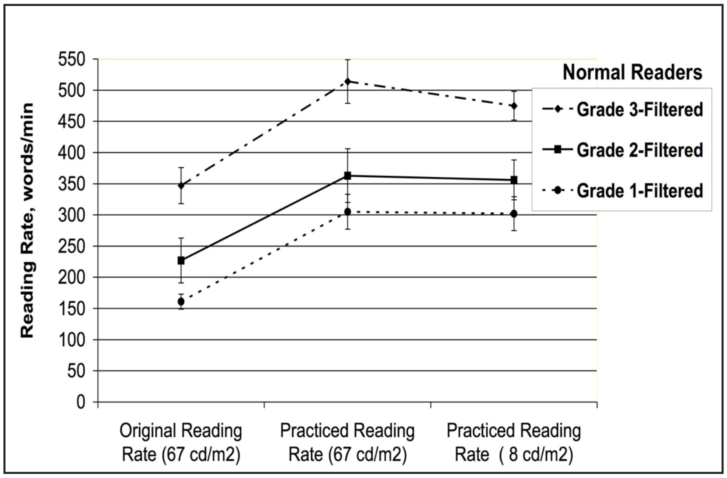

Figure 5a

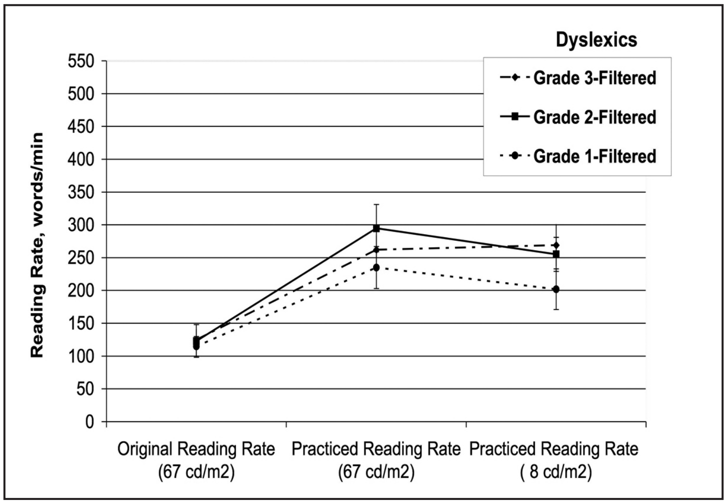

Figure 5b

Figures 5: *Reading rates for filtered text before and after direction discrimination training at both high and low mean luminance levels for both normal readers (5a) and dyslexic readers (5b).*

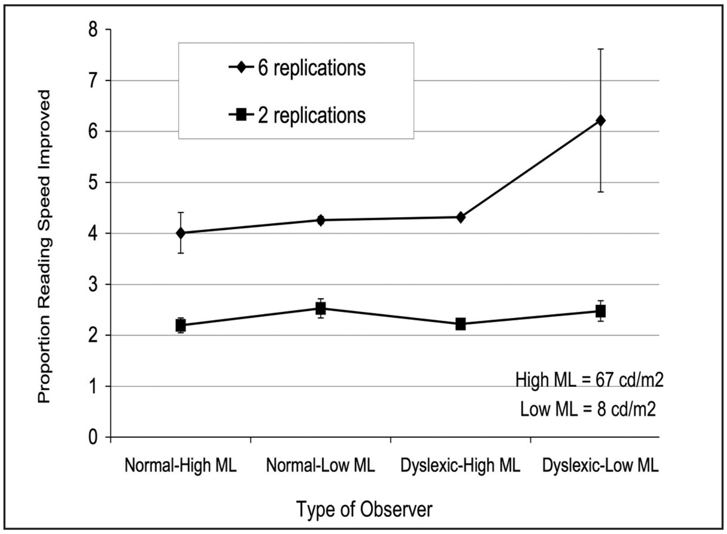

***Figure 6**: Proportionate improvement in reading speed (Final Reading Rate / Initial Reading Rate) for 6 replications (2 dyslexic and 2 normal readers) and 2 replications (7 dyslexic and 8 normal readers) after training on direction discrimination, at both High and Low Mean Luminance (ML).*

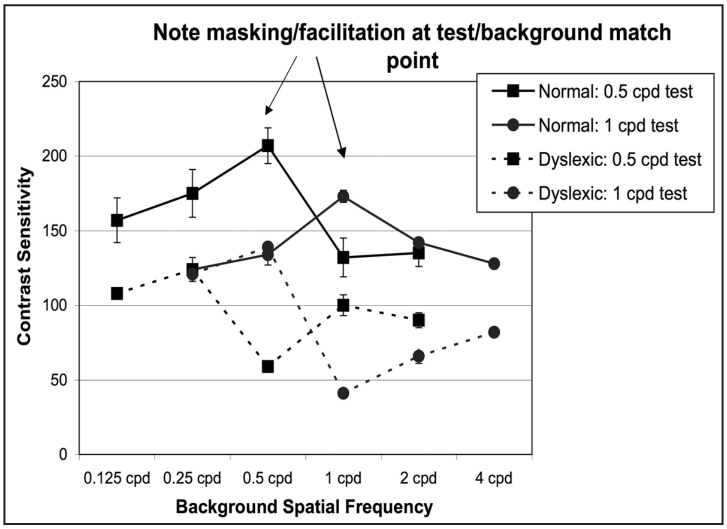

***Figure 7**: Mean practiced CSF for 0.5 and 1 cyc/deg test frequencies, when averaged across grade levels.*

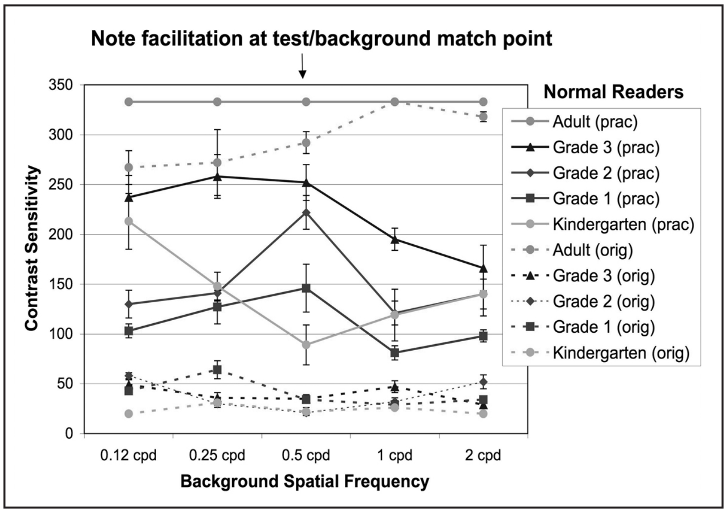

Figure 8a

Direction discrimination is developing in children 5-8 years old

The direction discrimination CSFs were more sensitive as the grade level increased for efficient readers, Fig. 8a, being highly significant, $p < 0.001$, when analyzed using a repeated-measures 2 factors ANOVA. On the other hand, these CSFs were not significantly different at different grade levels for dyslexics, Fig. 8b. The direction discrimination CSFs for children in Kindergarten were lower than the CSF of normal readers when test and background frequencies were equal (Fig. 8a), and were not significantly different from the CSFs of dyslexic readers (Fig. 8b). The direction discrimination network,[19] consisting of cortical areas V1 (striate cortex) and Medial Temporal Cortex (MT), seems to be developing normally only for normal readers. Direction discrimination is developing in children aged 5 to 8 years, a key time of cortical plasticity that occurs during normal development[20] when the child is learning to read,[3] and is significantly less sensitive in children than for adult readers, $p < 0.0001$. CSFs improved an average of four-fold for normal readers and five-fold for dyslexics following training on direction discrimination, showing rapid perceptual learning in children aged 5 to 8 years.

Achromatic text was read much faster than colored text

Equiluminant chromatic text was read much more slowly than achromatic white text, (Table 3). Both dyslexic and normal readers read both filtered (Fig. 9) and unfiltered chromatic text more slowly. Moreover, reading rates were 30% slower when colored text was presented on opponently colored backgrounds, *e.g.* red text on a green background, or blue text on a yellow background, than when presented on black backgrounds.

The differences in reading speeds, for both normal readers and dyslexics, between both unfiltered and filtered achromatic and chromatic text, was highly significant, ($p < 0.0001$) when analyzed using paired comparison *t*-tests, or the nonparametric Mann-Whitney *U* test. There were no significant differences in the reading speeds between different types of colored text, when analyzed using a one-factor ANOVA, or when analyzed using paired comparison *t*-tests.

Table 3. Reading Rates of White vs. Chromatic Text, *i.e.* (Reading Speed of White Text) / (Reading Speed of Chromatic Text) and Significance Levels for Normal and Dyslexic Readers for Unfiltered and Filtered Text

Normal Unfiltered	Red Text	Yellow Text	Green Text	Blue Text
Grade 3	1.34***	1.29***	1.29***	1.29***
Grade 2	1.57***	1.29***	1.47***	1.32***
Grade 1	1.62***	1.73***	1.55***	1.67***
Normal Filtered	Red Text	Yellow Text	Green Text	Blue Text
Grade 3	1.32***	1.77***	1.60***	1.49***
Grade 2	1.33***	2.07***	1.41***	1.45***
Grade 1	1.81***	1.62***	1.73***	1.35***
Dyslexic Unfiltered	Red Text	Yellow Text	Green Text	Blue Text
Grade 3	1.35***	1.37***	1.64***	1.31***
Grade 2	1.35***	1.33***	1.31***	1.36***
Grade 1	1.43***	1.41***	1.43***	1.43***
Dyslexic Filtered	Red Text	Yellow Text	Green Text	Blue Text
Grade 3	1.63***	1.76***	1.33***	1.47***
Grade 2	1.5***	1.62***	1.34***	1.37***
Grade 1	1.32***	1.89***	1.29***	1.29***

**** denotes $p < 0.0001$. There were 5 subjects in each group.*

Discussion

Filtered Text Improved Reading Fluency

Filtered text that compensates for contrast sensitivity losses provides a novel technique[1] in children for improving reading speed, in addition to direction discrimination training. This study found that after training on discriminating left-right movement, reading rates were at least 4 times faster when CSF losses were compensated for by the image enhancement filters. This indicates that children's CSFs for both orientation discrimination and direction discrimination are closely related to their reading performance.

The improved reading rates found with filtered text shows that spatial filtering is a powerful tool for improving children's reading performance. The Filters' transfer functions are designed to enhance degraded images by boosting the less visible spatial frequency components. Boosting the less visible spatial frequency components makes the pattern components in the spatial frequency band that is used for reading easier to see. This filtering approach compensates for the contrast that has been selectively reduced by the child's developing visual system. In children with reduced visual function, text prefiltering for contrast enhancement and presumably presents to the child's brain letters having spatial frequency components with the same relative amplitudes as those seen by a normal adult observer. In other words, precompensation filtering for a known degradation can be used to improve a child's reading performance.

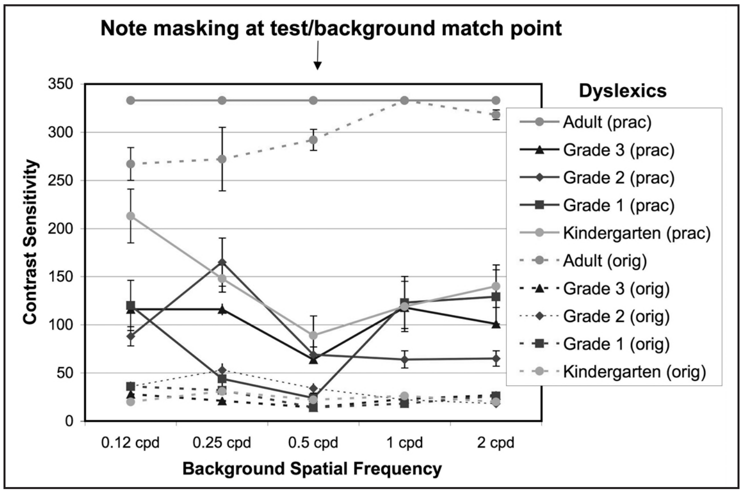

Figure 8b

Figure 8b *Mean Contrast Sensitivity Function (CSF) for normal readers (8a) and dyslexics (8b) when discriminating left-right movement of 0.5 cyc/deg test frequency relative to different background frequencies, before and after practice.*

These image enhancement filters are unique[2] and work well to improve the reading performance of observers with CSF losses compared to normal adults.[8] This includes children with and without dyslexia and adults with macular disease[8] These improvements with filtered text were found when portions of text were flashed on the screen for different durations and when text was scrolled across the screen.[8,16,18] Increased reading rates for filtered text were found for a wide range of people with contrast sensitivity losses when compared to normal adults, *e.g.* children aged 6-8 years who are normal readers, children who are dyslexic, and adults who have macular disease.[1,8,18] Since these filters are easily implemented using current digital technology on home computers, they offer a unique mechanism for helping a wide segment of the population read more easily.

Finding that reading speeds were not reduced at low mean luminance levels and that colored text was always read much more slowly than equiluminant

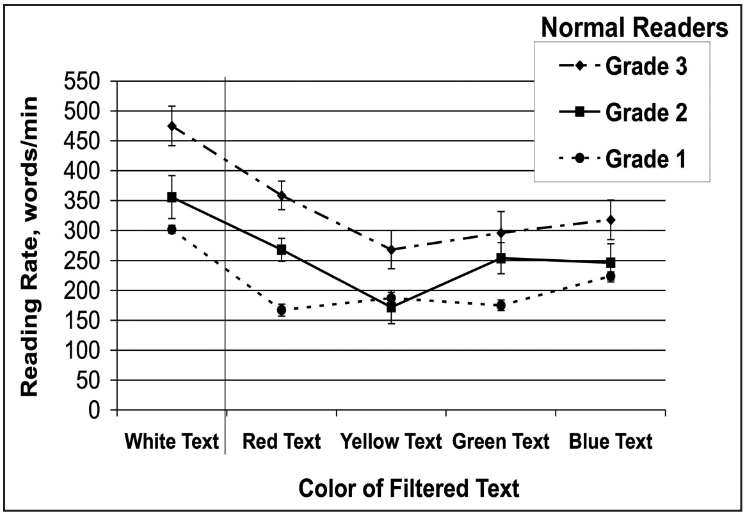

Figure 9a

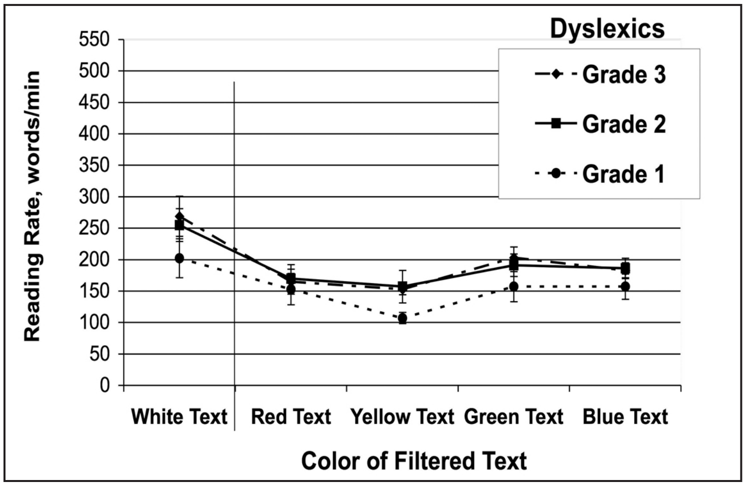

Figure 9b

Figures 9: *Reading rates for reading filtered grayscale (white) text as seen in Fig. 1 compared to reading rates for filtered colored text for normal readers (9a) and dyslexics (9b).*

grayscale text, provides further evidence that magnocellular pathways control reading fluency. Magnocellular neurons operate at low contrasts and low mean luminance levels,[9,21] and are essentially color-blind.[10] Since colored text always reduced reading speeds, this suggests that the effectiveness of the colored backgrounds produced when wearing Irlen lenses[11] to improve reading fluency is a result of reducing the contrast of the text, and not a result of adding chromatic information, as has been believed. This is validated further by the observation that reading rates were slowest when colored text was presented on colored backgrounds, as opposed to white or colored text presented on black backgrounds. Finding that reading rates are much lower when reading colored text supports previous controlled studies[22] that indicate that Irlen lenses do not improve a child's visual functions.

Direction Discrimination Training

Some dyslexic readers reported that when the background spatial frequency was equal to or higher than the test spatial frequency, the test frequency appeared to move back and forth, instead of moving in one direction. This perception disappeared after one month of training, so only one direction was seen. Noticeable improvements in reading accompanied the disappearance of this motion aftereffect, as reported by students and their teachers. It may be that the motion aftereffect disappeared as a result of improving the sensitivity of magnocellular pathways. This improved sensitivity would theoretically enable "tuning" the inhibitory pathways which suppress the motion aftereffect, thereby improving the timing between magnocellular and parvocellular activity. This improved timing, in turn, would lead to the improvement of most reading skills.[1-4] Dyslexics reported that initially, when the test and background frequencies were equal, the test and background patterns often seemed to blend together. This blending also disappeared after one month of training. This increased visible persistence for dyslexics was found previously.[23,24] These results suggest that dyslexic readers have not yet developed proper figure/ground discrimination easily, and that adjacent letters and words camouflage the word the dyslexic student is trying to read. This is otherwise known as lateral masking or crowding.[25] The data collected during this study from both normal and dyslexic readers, suggest that figure/ground discrimination is developing at the same time a child is learning to read.

Training on Direction Discrimination Improved Reading Fluency

The direction selectivity network,[19] consisting of cortical areas V1 and MT, provides the most likely circuit for magnocellular neurons' controlling reading fluency.[1-4] Both training on direction discrimination, activating the motion (magnocellular) circuits, and judging the direction of movement relative to a textured background, activating the linked pattern (parvocellular) circuits, are needed to improve reading fluency.[2,4] It is only on a textured background that people having visual and/or temporal processing issues, encompassing the three basic types of dyslexia, always show a motion discrimination deficit.[1-5] Finding that children who are dyslexic improve from two- to four-fold in reading fluency following training on direction discrimination[1,3] shows that dyslexic children employ perceptual learning. Since perceptual learning is gated by attention mechanisms,[26] these results suggest that the deficits in attentional focus experienced by inefficient readers result from an information overload and not from an inability to attend from some other source.[2,4]

By tuning low level directionally-selective motion mechanisms using sinewave gratings, it is as though a timing switch is turned on to facilitate learning reading skills.[3] The effectiveness of Direction Discrimination Training using sinewave gratings indicates that sinewave gratings may be optimal stimuli, where an optimal stimulus is defined as one that activates: 1) both low and high levels in the motion pathways by using the V1 - MT feed-forward and feedback pathways, and 2) both magnocellular (to discriminate movement) and parvocellular (to provide background frame of reference) neurons across a wide range of spatial frequencies. The direction discrimination CSF measured using sinewave gratings is more effective in differentiating between normal and dyslexic readers with both level and CSF shape differences (either convex upward or concave downward),[1,4] rather than the level difference that is found when discriminating the direction that random dot patterns have moved.[5-7,27] Moreover this training regimen 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.[3] Phonological language deficits might be remediated by tuning the lower cortical visual areas which, in turn, enable the higher language areas to be tuned, allowing the entire spectrum of reading deficits to improve significantly.[3]

In addition to presenting an optimal stimulus to activate both low and high levels of direction discrimination processing,[3] the patterns used in this study enabled measuring motion contrast thresholds, the key metric for direction discrimination.[28,29] This is in contrast to motion energy thresholds,[30] as measured when using random dot patterns. Moreover, random dot patterns are not analyzed until cortical area MT,[31] the motion center,[32-34] where differential sensitivity to these random dot patterns finally emerges.[35] Sinewave gratings, on the other hand, optimally activate all levels of visual processing beginning in the retina.

The training regimen used in this study should be more rapid and effective than methods that don't vary contrast to train motion discrimination, such as when measuring motion coherence thresholds.[7] This is due to contrast being directly related to the output of motion sensitive cells in the retina, lateral geniculate nucleus, and cortical areas V1 and MT.[9,21,36-38] Therapies that train direction-selectivity to remediate inefficient reading skills[1-4] are much faster and more effective over a wider spectrum of reading deficits than competitive therapies that only train phonological processing.[39-42]

Furthermore, the more training a child had on direction discrimination, the more reading speed skill improved.[1,3] This suggests that direction discrimination is linked to learning to read. Improving the gain (contrast sensitivity) and reducing the time to complete the task[3] suggests that this type of training improved the timing of magnocellular activity, so that it more readily brackets the linked parvocellular activity. This reduces the information overload, and improved reading efficiency.[3] Since magnocellular neurons control the gain of the direction-selectivity network,[19] the more sluggish, immature magnocellular neurons might be causing a deficit in attentional focus, preventing the linked parvocellular neurons from isolating and sequentially processing the relevant information.[3,43]

It seems likely that once direction discrimination is improved at low levels of visual processing in V1, then higher levels of processing in the motion system, like MT, where most cells are directionally-selective,[32,34] are also improved. Since cortical feedback from MT amplifies and focuses the activity of neurons in V1 that are used for figure/ground discrimination,[44] then increasing the activity of MT will improve figure/ground discrimination. The importance of feedback from MT is the most likely reason that the direction discrimination CSF improved the most for efficient readers when test and background spatial frequencies were equal.[1,3]

The inability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time, along with the lack of feedback from MT to improve the gain of direction selectivity, can be used to explain the spatial[27,45,46] and temporal[41,42,47,48] sequencing deficits, as well as the motion discrimination deficits[1-6,49-52] experienced by most dyslexic readers. By improving a child's contrast sensitivity for direction discrimination relative to a range of different patterned backgrounds, reading speed improved rapidly.[1-4]

Conclusions

Dyslexics can be differentiated from normal readers by their significantly lower sensitivity to the direction of movement. Following training on direction discrimination, contrast sensitivity functions improved an average of four-fold for normal readers and five-fold for dyslexics, showing rapid perceptual learning in children aged 5 to 8 years. Moreover, direction-discrimination training is a rapid and effective therapy for improving reading speed. The more training that a child had in discriminating the direction of movement, the more reading speed improved for both dyslexic and normal readers. This indicates that learning direction discrimination is linked to learning to read. In both the filtered and unfiltered cases, chromatic text was always read at least 30% more slowly than equiluminant achromatic text. This supports the theory that magnocellular activity influences reading speed more than parvocellular activity. Finding much faster reading speeds for filtered text, both before and after training on direction discrimination, shows the value of individualized contrast enhancement to improve reading skills. These image enhancement filters are unique[2] and work well to improve the reading performance of children. Both image enhancement and direction discrimination training offer great promise for improving reading fluency.

Note: PATH to Reading is now available as an inexpensive software program on either Macintosh or Windows computers.

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