Training directionally selective motion pathways can significantly improve reading efficiency

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ABSTRACT

This study examined whether perceptual learning at early levels of visual processing would facilitate learning at higher levels of processing. This was examined by determining whether training the motion pathways by practicing left-right movement discrimination, as found previously, would improve the reading skills of inefficient readers significantly more than another computer game, a word discrimination game, or the reading program offered by the school. This controlled validation study found that practicing left-right movement discrimination 5-10 minutes twice a week (rapidly) for 15 weeks doubled reading fluency, and significantly improved all reading skills by more than one grade level, whereas inefficient readers in the control groups barely improved on these reading skills. In contrast to previous studies of perceptual learning, these experiments show that perceptual learning of direction discrimination significantly improved reading skills determined at higher levels of cognitive processing, thereby being generalized to a new task. The deficits in reading performance and attentional focus experienced by the person who struggles when reading are suggested to result from an information overload, resulting from timing deficits in the direction-selectivity network proposed by Russell De Valois et al. (2000), that following practice on direction discrimination goes away. This study found that practicing direction discrimination rapidly transitions the inefficient 7-year-old reader to an efficient reader.

Many inefficient readers are dyslexic. Dyslexia is diagnosed when a child has normal or above-normal intelligence, yet fails to acquire efficient reading skills, despite extensive educational training. Inefficient readers often lose their place in the text when reading, unless a finger or pointer is used to guide their eyes. Inefficient readers are reported to have some combination of spatial (1-4) and/or temporal (5-7) sequencing deficits, causing the letters in the words and the words on the page to appear displaced, or crowded together (8). 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 (9).

Many inefficient readers also have motion discrimination deficits, including an impaired ability to discriminate both the direction (10-14) and the velocity (15,16) of visual patterns. Moreover, the more direction discrimination was practiced, the faster was the speed used to read continuous text (12). This pilot study (12) showed that direction discrimination was linked to reading ability. This finding is remarkable, since previous investigations have shown that rarely does perceptual learning generalize to a new task, that is, it is specific for the trained task (17-19).

Therefore, it was essential to conduct a controlled validation study to determine whether practicing direction discrimination {MovingToRead (MTR) therapy} would improve reading fluency for inefficient readers more efficiently, than another computer game, a word discrimination game, compared to children who only received the school's reading program. The MTR therapy was designed to train directionally-selective motion pathways, the 'where' or dorsal visual pathway (presumably processing the location of letters in a word, and the words on a page), and the word discrimination game was designed to train the 'what' or ventral visual pathway (presumably processing what type of word was presented, *eg.* Was it an animal name, a person's name, or a nonsense word?). These dorsal and ventral pathway functions were first described by Ungerleider and Mishkin (20). The current study focuses on 7-year-old students, since children in this age group are in a period of peak developmental plasticity for learning to read, when the temporal and frontal lobes have maximal synaptogenesis (21). This study provides further support that the task of learning to discriminate the direction of movement is critical to the act of reading and is not a part of the eye-brain function that we are born with, but is a skill that must be learned (12).

METHODS

Procedures

The MTR therapy was used in controlled clinical studies during the school year 2002-2003 in three elementary schools in the Santa Monica and Los Angeles Unified School Districts following approval by school administrators, and after informed consent forms, approved by the Independent Review Consulting Institutional Review Board (IRB), were signed by each parent and student who participated in this study. The Dyslexia Determination Test (DDT; 9) was used to

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classify each student as an inefficient reader. Based on the DDT, 33 inefficient readers in second grade, most being 7-years-old, were included in this study. Only students who had no known visual or neurological deficits were included. The students, who all received the regular school reading program, were randomly assigned to one of 3 groups using a matched-sample design, based on the results from the standardized tests. More children were assigned to the treatment group, to ensure that the school found this intervention training improved reading scores overall, and was worth the time being taken away from other activities.

The subject selection procedure resulted in an ethnic distribution consisting of an approximately equal number of male and female students, having the following ethnic and racial distribution: 19% Hispanic, 62% Caucasian, 11% Asian, and 8% African American students. The 33 inefficient readers who completed this study were distributed across the 3 groups as follows: MTR therapy: 18, word game: 9, no game: 6; for efficient readers. There was some drop out due to moving away, excessive absenses, and physical injuries that damaged visual sensitivity. To ensure there were sufficient inefficient readers in the matched-sample, only inefficient readers who were diagnosed with borderline or mild dyslexia were included in this study. Even though these students were classified with borderline or mild reading issues, all inefficient readers struggled with reading. Students received instructions that were comprehensive and standardized by watching Quicktime movies (4 min) to learn how to play both the reading speed and the two different computer games.

All training of students, supervising the computer games, and measuring reading fluency was performed by reading assistants (pre-optometry students at UCLA), to ensure that this study was run in a blind manner. Neither the reading assistants, nor the classroom teachers were aware of which game might improve reading performance the most. The reading assistants knew which students belonged to which groups, but were instructed to treat the two groups equally, and in any case could not encourage them more on a particular therapy, because they did not know the significance of the therapies. Moreover, if asked, the reading assistants were told that the word discrimination game was similar to standard procedures used to remediate reading problems. Thus, most thought that the word discrimination game was used for the treatment group.

Moreover, information about the techniques being used for remediation by Perception Dynamics Institute, now available on the website: www.movingtoread.com, was not available until July 2003, after this study was completed. The battery of psychometric tests of the literacy components used for reading were administered by the reading assistants to each student at the beginning and end of this study. The data with date and time stamps in several files in different folders were collected automatically by computer programs, so that once data was collected by the computer, there could be no influence on the results.

Two of the three groups played a computer game, either word discrimination or left-right movement discrimination. The word discrimination game was a control therapy with high face validity for potentially improving reading skills, even though the experimental test of movement discrimination was the one that had been shown to be most effective in pilot studies. The third control group of inefficient readers was not pulled out of class to play a 10-minute computer game. The computer game was either played in the classroom for 2 of the 3 elementary schools, or in the computer lab in the other elementary school. IMac computers, supplied either by Perception Dynamics Institute, or the elementary school, were used in all 3 schools for playing the computer games. The intervention therapies were administered between 8:15 to 10:10 AM in all 3 elementary schools, enabling each child to have plenty of opportunity, following practicing discrimination on the computer, to practice reading during the school day. The computer games, which were started in January and finished in May, were played twice a week for 15 weeks, although not always consecutively due to holidays and planned school activities. The data were analyzed at the end of this study using the Excel Data Analysis software toolkit, including one-factor, and two-factor with replication, Analysis of Variance (ANOVA) statistical tests to determine whether the differences between treatment and control groups were significant. One-factor ANOVAs were used to examine whether the improvements in the treatment group were significantly different from the improvements in the control groups when unequal sample sizes were used in the data analyses. Two factor ANOVAS with replication require equal sample sizes.

Psychometric Tests of Literacy

During this validation study, standardized tests of reading skills were administered to every student in the study, both initially and at the end of the study, to measure their improvements in the perceptual and cognitive components used in reading. These tests included: DDT to test phonological and orthographic skills, and sight-word reading grade-level; Wide Range Achievement Test (WRAT-3) to test reading (word identification) and spelling; Wechsler Intelligence Scale for Children (WISC) Coding subtest to test copying; Gray Silent-Reading Test (GSRT) to test reading comprehension; and Computer-Based Reading Speeds to assess reading fluency. The WRAT-3 and DDT both measured reading grade level to provide two independent measures, and provide further validation for the DDT to classify inefficient readers. Tests of visual skills were measured by local optometrists to ensure that each child had normal visual functions. The entire battery of psychometric tests took approximately one hour to administer to each student.

The raw score on each reading skills test corresponded to a standardized score and an equivalent grade level, where a grade level of 1 is composed of 6-year-old students, a grade level of 2 for 7-year-old students, and so forth. The equivalent grade level was used to plot the initial and final reading scores, and measure the amount of improvement, on each of the psychometric tests of literacy, since grade level was the most relevant information for teachers and school administrators. The relative improvement in reading skills was determined by comparing the difference between final and initial grade levels.

Computer-Based Reading Speed

Reading fluency, or how fast a child is able to read aloud, was used to provide baseline data at the beginning of this study, and to determine improvements in reading speed at the end of the study. This task to measure reading speed flashed 6 words of continuous text for different durations from an interesting, easy-to-read story, *i.e. Frog and Toad* by Arnold Lobel. Continuous lines of text that never repeated were presented on the display six words at a time, so that there was no crowding from adjacent words above or below the line being read, and at least one saccade was required to read each line of text. Large (0.5 cm wide by 0.5 to 0.75 cm high) white *sans-serif* letters, presented on a black background were used to test reading rates. The six words of white text were centered in a black window, 1.5 cm high by 14.5 cm wide, for maximal contrast. The black window was centered in the display window that was set to the mean luminance of 50 cd/m^2. The child could read the six 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 experimenter chose a rate of text presentation that was continuous and comfortable for the child. Initially the speed of presentation was increased from 40 words/min until five out of six words were not read correctly and in the correct order. At the first incorrect response, a double staircase procedure was implemented, decreasing the speed by 1 step each time the text was not correctly identified, and increasing the speed 1 step only when the child correctly read subsequent lines of text three times in a row. This task consisted of coached reading where the child was corrected when pronouncing a word incorrectly, and was asked to repeat only the words missed during the last reading of 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. The mean reading-speed threshold was computed from two threshold measurements, each consisting of approximately 20-30 trials. This task took 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 could be used to normalize the amount of improvement.

MTR Therapy: Left-Right Movement Discrimination

The patented MTR therapy (12) consists of a striped-fish pattern that moves to the left or to the right in the center of a striped background, see Fig. 1. The test spatial frequency jumps either 90 deg, the optimal phase difference for discriminating direction of movement (22), to the left or to the right, determined randomly, between the first and second pattern interval, as described previously (22). In this study, three, instead of two pattern intervals were used to increase the total duration of the motion stimulus from 300 to 450 msec. The child plays the 'fish game' by pushing an arrow key to indicate the direction the fish stripes are moving. Each time the child correctly identifies the direction the fish stripes moved, the contrast of the stripes gets progressively fainter, in steps of 0.3% contrast down to a step size of 0.1% contrast, until the child is unable to determine which way the stripes moved. Following the first incorrect response, a two-alternative forced-choice double-staircase procedure (22) is used to measure the most sensitive, repeatable direction discrimination contrast thresholds. When the direction is not seen correctly, the contrast of the stripes gets darker and a short auditory signal warns the child that the wrong button was pushed. Auditory feedback helps the child learn the game quickly. The direction has to be seen correctly three times in a row before the contrast is reduced one step. This staircase procedure measures the contrast needed for 79% correct responses. The MTR therapy measures a child's ability to see these subtle movements and tracks the child's improvement in direction discrimination over time.

The stimulus used for practicing left-right movement discrimination (see Fig. 1) consisted of one from a range of low test spatial frequencies (0.25, 0.5, 1, and 2 cyc/deg) surrounded by one of a 4-octave range of background spatial frequencies, either equal to the test frequency or 1 or 2 octaves (doubling in frequency) higher or lower than the test frequency, to examine a wide range of test-background frequency combinations, centered around each test spatial frequency. Initially both the test and background frequencies were set to 5% contrast, to ensure they were presented well above contrast threshold, yet low enough in contrast so that direction-selectivity was optimized, as found previously

(26). Three consecutive 150 msec time intervals were used to present leftward or rightward movement to ensure that a long duration dynamic stimulus was used, and to ensure this task was easier for inefficient readers, as found in pilot studies, enabling the game to be learned more quickly.

A full cycle of the left-right movement discrimination task is composed of a set of 20 threshold determinations, five each for the four test spatial frequencies of 0.25, 0.5, 1, and 2 cyc/deg. Each session consisted of 10 contrast thresholds, involving two ‘test’ frequencies (in the center of the display) and five background spatial frequencies, ranging in octave intervals from -2 to +2 octaves in spatial frequency from the ‘test’ frequency, see Fig. 1. The test was conducted, for each of two test spatial frequencies, 0.5 and 1 cyc/deg one day, and 2 and 0.25 cyc/deg the second day during the 15 weeks of this study. This order for presenting the test frequencies was chosen to gradually increase the difficulty of the task, thereby increasing motivation to continue playing, with a 0.5 cyc/deg test being the easiest for judging the direction of movement, and 0.25 cyc/deg being the most difficult, as discovered in the pilot study (12). Each threshold required 20-30 trials to complete. A score was given to make the intervention therapy more game-like, and provide more motivation. The lower the contrast threshold, the higher was the score.

Two Contrast Sensitivity Functions (CSF) were computed to evaluate the effectiveness of training direction-selectivity. The initial direction discrimination CSF was determined by the maximum contrast sensitivity after completing the first two replications. The final CSF was the maximum contrast sensitivity to discriminate the direction of movement for each test-background pattern combination at the end of this study.

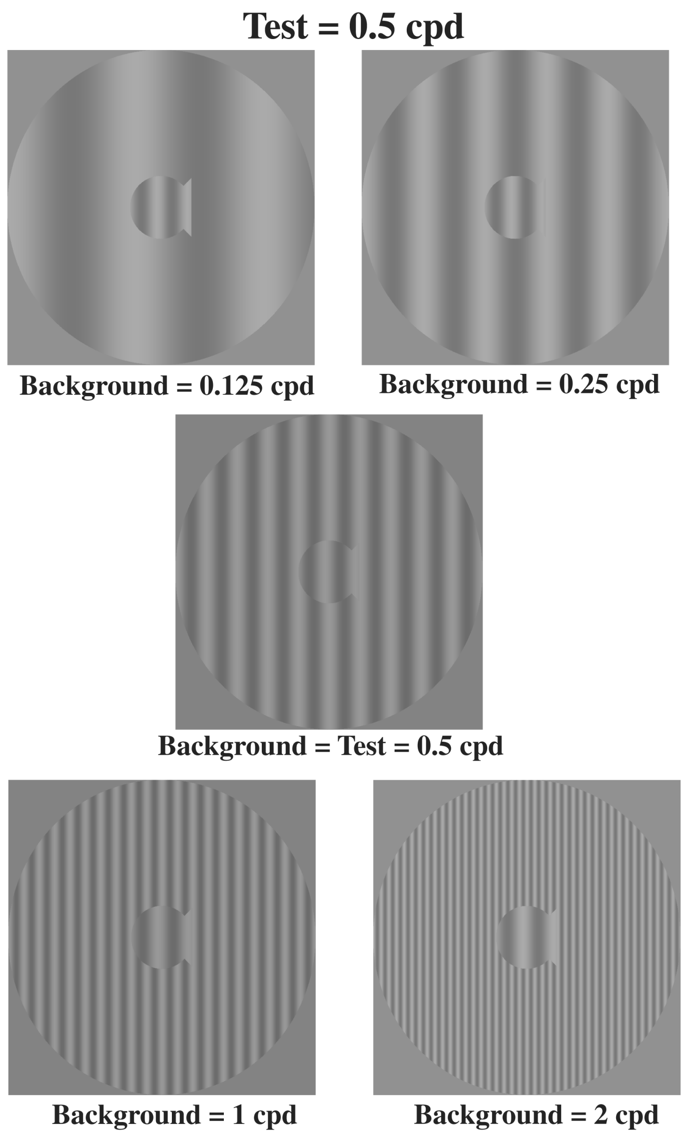


Fig. 1. Sample patterns for test frequency = 0.5 cyc/deg (cpd) on Different Backgrounds

Word Discrimination Game

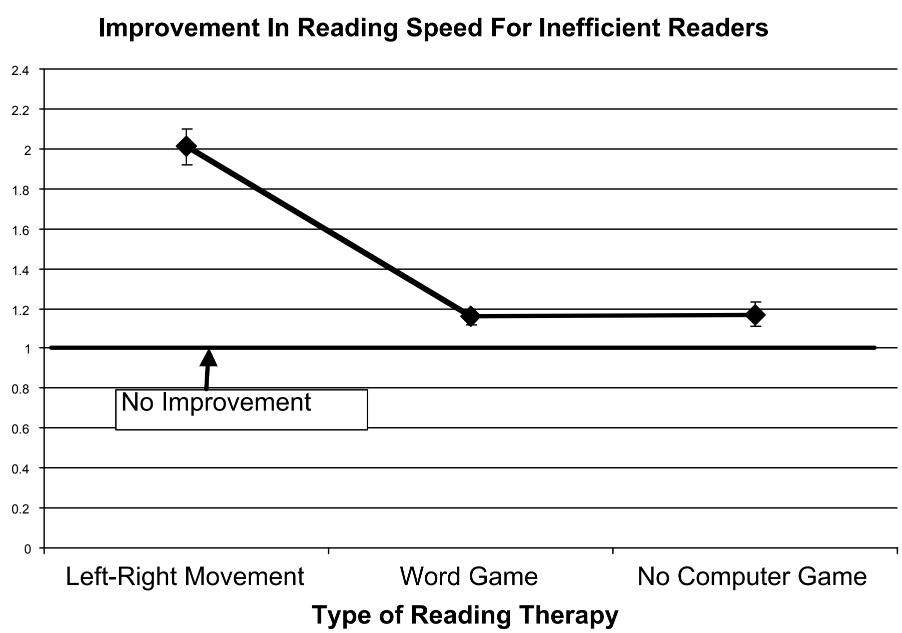
One group of inefficient readers practiced a word discrimination game (control group) twice a week, each session lasting around ten minutes. There were 3 different word discrimination games, to keep the students in a high motivational level, each played on a separate day. The first game was the animal game, where 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 game was the name game, where the right arrow key was pushed if the word was a person's name, and the left arrow key otherwise. All words were in lower case letters. The third game was the nonsense game, where the right arrow key was pushed if the word was a nonsense word, and the left arrow key otherwise. The child got a score of 5 points for correctly pushing the left arrow key, 2 points for correctly pushing the right arrow key, and lost a point for pushing the wrong key. The word was presented on the screen until the child pushed either the left or right arrow key, a '+' or '-' appeared in the middle of the screen above where the word just disappeared, and the score was displayed in the upper right corner of the window. These instructions appeared in writing at the beginning of each word game.

RESULTS

At the beginning of this study, no significant differences were found between the 3 groups (left-right movement discrimination, word discrimination, no computer game) of inefficient readers, on any of the tests of reading skills. These results were analyzed using a one-factor ANOVA statistical test. Thus, each of these three groups were matched samples. ANOVA statistical tests found that there were no significant differences in the initial reading speeds between these two groups, providing further support this was a matched sample design.

The prevalence of dyslexia depends on a number of factors, *e.g.,* how it is defined and tested, and on whom. Instead of an expected prevalence of approximately 10% (11), dyslexia that included borderline and mild levels was diagnosed in 35% of the 7-year-old children tested in 3 elementary schools in the Los Angeles area.

The results of this controlled validation study found that most inefficient readers who practiced left-right movement discrimination doubled their reading speed, this improvement was highly significant [F_2=31.55, sig@ $p < 0.0008$] when analyzed using a one-factor ANOVA, when compared to the improvements in the reading speeds of the other two groups of inefficient readers, who barely increased, see Fig 2. The improvement in reading speed was calculated by dividing the final reading speed by the initial reading speed, to determine the child's proportionate improvement in reading speed. Therefore, a value of 1.0 shows no improvement. The error bars in all figures correspond to ± the standard error of the mean amount of improvement.



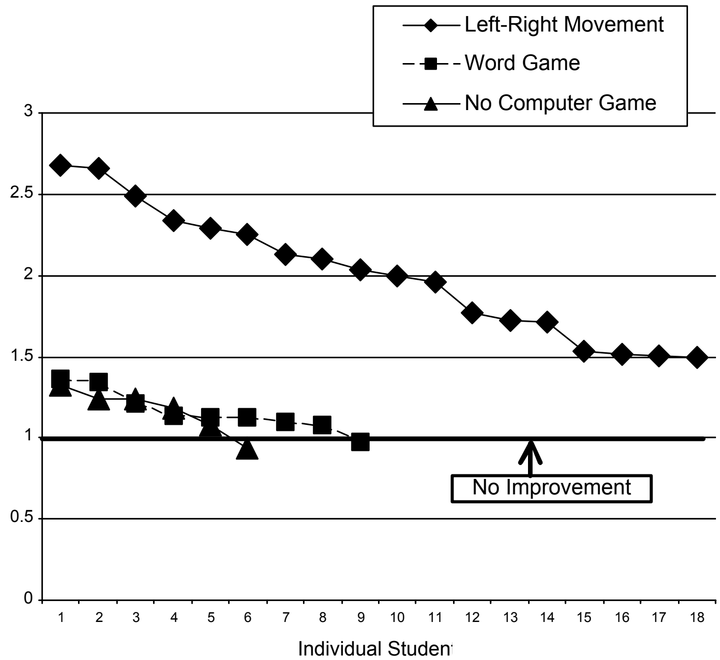


Fig 2. Mean (2a) and individual (2b) improvements in reading speeds for the 3 groups of inefficient readers.

Some children when discriminating the direction of patterns having equal test and background frequencies, saw the test pattern oscillate from side to side and not move in one direction. This motion aftereffect always disappeared after 10 practice sessions, about one month later, as found previously (12). Following the first few sessions, all students had learned the direction discrimination task and did not need individual supervision. In fact, most students understood the task after watching the 4 min Quicktime movie.

Inefficient readers who practiced left-right movement discrimination increased by more than one grade level on a wide range of reading skills (see Fig. 3). This improvement was significant for reading grade level [F_2=6.13, sig@ $p< 0.006$], word identification [F_2=4.78, sig@ $p< 0.016$], spelling [F_2=3.65, sig@ $p < 0.038$], copying [F_2=4.04, sig@ $p < 0.028$], and reading comprehension [F_2=4.45, sig@ $p < 0.02$], determined separately using a one-factor ANOVA, to analyze the entire matched sample of inefficient readers. The amount of grade level improvement was determined by computing the difference between the final and initial grade levels, provided by standardized psychometric scores on each of the five reading tests. The mean initial and final grade levels and the range of improvements in grade level for each of the tests of reading skills for inefficient readers who practiced direction discrimination are listed in Table 1. On the other hand, children who were not pulled out of class to play a computer game, or who played the word discrimination computer game barely improved on these reading skills, see Fig. 3. Finding that only inefficient readers who practiced left-right movement discrimination improved significantly on a wide range of reading skills indicates that: 1) inefficient readers have immature directionally-selective motion pathways, and 2) learning directionally-selectivity movement discrimination is linked to efficient learning of reading skills.

Table 1. Average Grade Level (GL) and range of improvement on each of the reading skills tests for inefficient readers who practiced direction discrimination.

Reading Skills Test	Initial GL	Final GL	Min GL Improve	Max GL Improve
DDT Reading GL	2.9	4.3	0	2
WRAT Reading GL	2.7	3.9	0	2.7
WRAT Spelling GL	2.1	3.3	0	1.9
WISC Copying GL	2.3	3.8	0.3	3.4
GSRT Comprehension GL	0.8	2.1	0.1	2.9

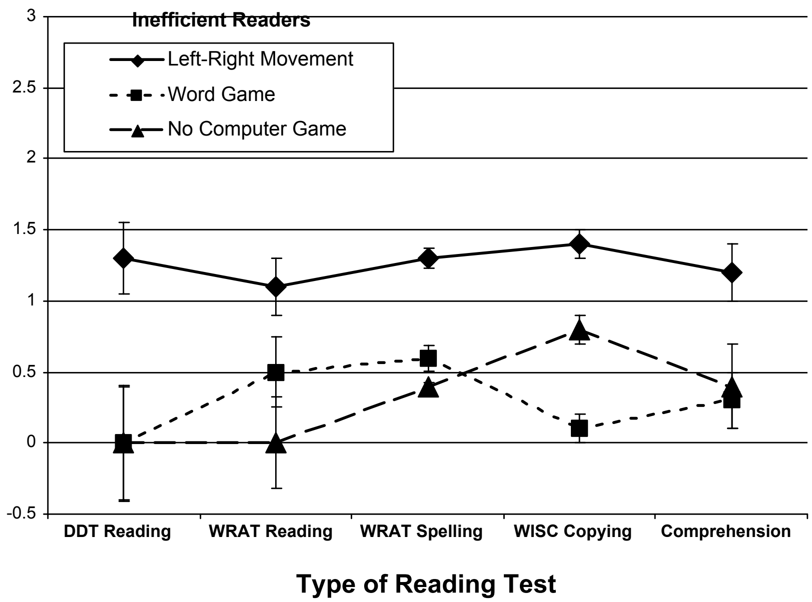


Figure 3. Improvements in reading skills for inefficient readers in the 3 different groups.

When the amount of improvement on the 5 reading tests were analyzed together across the 3 groups, using a two-factor ANOVA with replication, thereby increasing the power of the analysis, the significance in the amount of grade level improvement in reading skills for children who practiced direction discrimination was highly significant, [F_2=11.13, sig@ $p < 0.000006$]. Moreover, there were no significant differences between the different reading tests within each group, showing each group had the same relative grade level improvement across reading tests. Since equal sample sizes were required to use a two-factor ANOVA, six equally-spaced individual amounts of improvement in grade level on each of the five reading tests (DDT Reading, WRAT Reading and Spelling, WISC Coping, and GSRT reading comprehension) were analyzed. To ensure that the reduced sample had the same distribution of relative improvement scores as did the original sample, the 18 samples of inefficient readers were reduced to 6 samples in the following manner: 1) Order amount of improvement from most to least, and 2) Choose the middle sample from each 3 adjacent samples. The mean amount of grade level improvement in reading skills of this reduced sample always equalled the mean amount of improvement for the entire sample, showing that the reduced sample was representative of the entire sample. A similar procedure was used to reduce the 9 samples for children who played the word game down to 6 samples.

Following a short amount of practice (30 5-10 minute sessions), inefficient readers improved four fold, on average in discriminating the direction of movement. The maximum CSF for direction discrimination improved significantly [F_1=23.06, sig@ $p < 0.0001$]. Following practice, the direction discrimination CSFs of inefficient readers rapidly transitioned to the CSFs of efficient readers. As the intervention training progressed over time, not only did the child's contrast sensitivity for direction discrimination improve significantly, but the time taken to practice left-right movement discrimination was reduced in half. These results show that inefficient readers are not only attending to the task, but also strengthening the directionally-selective motion pathways, and improving on a wide range of reading skills.

DISCUSSION

This study found that training children to discriminate the direction of movement (MTR therapy) for 5-10 minutes twice a week for 15 weeks significantly improved the literacy skills required for efficient reading, for all types of inefficient readers, *i.e.,* those having both phonological and/or orthographic reading issues. On the other hand, inefficient readers who practiced discriminating between different categories of words, or who only received the school's reading program barely improved at all on the 5 measured components of reading skills. This study demonstrates that learning direction discrimination is linked to learning to read.

It is remarkable that the MTR therapy is so rapid, a total of 4 hours, when other well documented reading remediation therapies, *e.g.,* (23,24), take at least 50 hours. Moreover, these reading therapies only remediate phonological deficits and require one-on-one instruction throughout the therapy. Therefore, this therapy is not only limited to one type of reading deficit, time intensive, but it is also costly to administer. Furthermore, the amount of improvement after 100 hours of reading therapy was equivalent to that found after 50 hours (23). The improvement in reading skills found following the MTR therapy, on the other hand, does not have these limitations. The more direction discrimination was practiced, the more the child improved in reading fluency (12). The MTR therapy is the first technique that has been found to rapidly remediate a wide range of reading issues, especially poor reading fluency, for children having both phonological and/or orthographic processing deficits.

Cortical plasticity of directionally-selective motion pathways

If timing deficits in the response characteristics of magnocellular neurons prevent a child from developing efficient reading skills, as proposed by many (2,10-12,25), then training observers using a task found to improve one's sensitivity to the direction of movement (12,17,26) should improve the reading skills of inefficient 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 (27). The results from this study, and found previously (12), show that when varying contrast sinusoidal gratings that optimally activate the direction-selectivity channels are used for measuring sensitivity to direction of movement, tuning up the center of the working range for motion discrimination at both low levels (cortical area V1) and high levels (cortical area MT) of visual processing, then reading inefficiencies are remediated rapidly for a wide range of inefficient readers.

The stimulus used in this study for practicing left-right movement discrimination (see Fig. 1) was previously found to be optimal for measuring sensitivity to direction-selectivity (22,26). The procedure for determining optimal activation of direction-selective magnocellular streams was as follows: 1) Sinewave gratings, instead of random dots, were used to train the direction-selectivity pathways, since perceptual learning is over 10-fold faster when discriminating the direction of sine-wave gratings (17) than for random dot patterns (18). 2) The test sinewave grating jumped 90 degrees (deg) between the first and second pattern interval, since this is the optimal phase difference for direction discrimination (22). 3) A range of test frequencies (0.25, 0.5, 1, and 2 cyc/deg) were used to span the spatial frequencies that predominantly activate magnocellular streams (29-31). 4) A 4-octave range of clearly visible background spatial frequencies, set to 5% contrast, centered around the test spatial frequency was used to map out each channel's spatial frequency tuning function. These background frequencies were an octave apart, since perceptual learning of direction discrimination does not transfer to frequencies differing by more than one octave (17), 5) Initially, both the test and background sinewave gratings were presented at 5% contrast, so that these patterns would optimally activate magnocellular neurons (31). 6) The Contrast Sensitivity Function (CSF), which is 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 direction-selective cell (32). 7) To prevent saccadic eye movements from being involved, left-right movement was presented by having the test sinewave grating jump left or right (determined randomly) in 150 msec pattern intervals, since saccadic programming takes around 150 msec (33). This design prevented express saccades (34) from contributing to direction discrimination. Three consecutive 150 msec time intervals were used to present leftward or rightward movement to ensure that a long duration dynamic stimulus was used, thereby activating both magno and parvo streams.

In addition to presenting sinewave gratings that jump 90 deg relative to a background grating, thereby providing an optimal stimulus at both low and high levels of motion processing, variable contrast sinewave gratings moving relative to a background grating enabled measuring motion contrast thresholds, the key metric for direction discrimination (35,36), rather than motion energy thresholds (37), as measured when using random dot patterns. The motion coherence task, determining the direction random dot patterns moved, on the other hand, activating only complex cells (38), is not analyzed until area MT (39), the motion center (32,40), where sensitivity to the global direction of coherent motion finally emerges (41).

Since this study found that when mild and borderline levels of reading problems were included, then 35% of the 7-year-old children showed at least some degree of dyslexic coding patterns, this indicates that reading problems are a much larger issue than addressed by only including inefficient readers who are markedly below normal, as is currently done when concluding that only 10% (11) of the children are dyslexic.

Previous investigations have shown that rarely does perceptual learning generalize to a new task, that is, it is specific for the trained task (17-19). This study, in contrast, demonstrates that practicing left-right movement discrimination for inefficient readers leads to significant improvements in reading efficiency (over a grade level on a wide range of literacy skills), as well as an average doubling of reading fluency, which includes both reading-speed and comprehension. Moreover, tuning up the center of the direction discrimination working range at both low and high levels of visual processing was not only very effective, but also much more rapid than competitive therapies (23,24) to remediate inefficient reading skills.

The MTR therapy is synergistic with ***both*** phonemic/phonological awareness and orthographic coding, unlike competitive therapies (23,24). Perhaps the two major subtypes of dyslexia, expressed as deficits in phonological and/or orthographic skills, are expressed differently depending on additional factors such as genetics, as has been suggested previously (11,42).

The MTR therapy reinforces the brain's ability to discriminate the direction of movement. The large differences between the direction discrimination CSFs for inefficient and efficient readers found in this study and previously (12) provide substantial support that magnocellular streams control reading fluency, these pathways being immature in dyslexic readers.

Training motion pathways remediates reading problems

The direction-selectivity network, a key attribute of neurons in the motion pathway, located in layers 4b and 6 in cortical area V1, consists of temporally biphasic even-symmetric magnocellular neurons that are linked to monophasic odd-symmetric parvocellular neurons (43). Even though the timing of visual events in the direction-selectivity network is signaled by biphasic even-symmetric magno neurons, the background frame of reference is signaled by monophasic odd-symmetric parvo neurons in layer 6 of area V1 (43), as first suggested to explain direction discrimination in normal observers relative to a multifrequency background (26). The monophasic odd-symmetric parvo neurons are activated between the first and second phase of the biphasic even-symmetric magno neurons (43). To detect the direction of movement, the magno neurons, providing the temporal frame of reference, bracket the activity of the parvo neurons that provide the spatial frame of reference. Only pyramidal neurons in layer 4b in cortical area V1 receive inputs from both parvo and magno neurons, whereas stellate and inhibitory neurons only receive inputs from magno neurons (44). Therefore, although magnocellular inputs predominate in the motion system (27,29,43), inhibitory interactions being mediated solely by magno neurons, the textured background that serves as the spatial frame of reference for judging left-right movement is analyzed by the output from parvo neurons (43). It is interesting to note that the parvocellular neurons provide a relatively small contribution to the motion system. Yet the inability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time is the most likely explanation for the mechanism that has not yet developed in dyslexic individuals.

The sluggish magnocellular neurons found in the LGN, and cortical areas V1 and Medial Temporal Cortex (MT), for inefficient readers (15,16,25) would make it difficult to attend in a direction discrimination task, since the biphasic magnocellular neurons would not signal V1 neurons in advance of the parvocellular neurons. Since magnocellular neurons control the gain of the direction-selectivity network (43), the more sluggish, immature magnocellular neurons might be causing a deficit in attentional focus, preventing the parvocellular neurons from isolating the relevant information. Therefore, the frame of reference would not be demarcated so that the position of the letters in the word, and the words in the text could be read easily. In fact, inefficient readers have an impaired focus of attention (45,46) spending a longer dwell time on each word, using an increased number of saccades and regressions to read text that is not due to an oculomotor control deficit (47).

The inability of magnocellular neurons to bracket the activity of linked parvocellular neurons over time can explain the spatial (1-4) and temporal (5-7) sequencing deficits, as well as the motion discrimination deficits (10-16) experienced by most inefficient readers. This study demonstrates that improving the sensitivity of inefficient readers to visual motion by practicing direction discrimination improves both orthographic skills (requiring accurate spatial sequencing) and phonological skills (requiring accurate temporal sequencing). These results provide further support that immature magnocellular streams underlie the reading deficits of inefficient readers.

There are some studies (48,49) that refute the contribution of magno deficits to explain the mechanisms underlying dyslexia. At the heart of this controvery is a methodological one where the patterns used to diagnose motion deficits in inefficient readers are not optimal for detecting the type of motion that is relevant to reading. Sensitivity to flicker, *e.g.* counter-phase gratings, or detecting short duration patterns less than 50 msec, neither being an optimal stimulus for activating direction-selective cells (26, 43,50,51,52), counterphase gratings requiring twice as much contrast to detect motion (51,53), compared to sinewave gratings that move in one direction, is the dependent variable measured in studies that refute the contribution of magno deficits (48,49) to the reading problems of inefficient readers. Moreover, it is likely that flicker only requires excitatory pathways, whereas direction discrimination requires both excitatory and inhibitory pathways (43).

Studies that find only a portion of dyslexic readers exhibit motion deficits (1,4,14,54) measured the direction of movement relative to a uniform field instead of a textured background. A normal observer's sensitivity to motion is enhanced when judging the direction of movement relative to a structured textured background (26,55). When the contrast sensitivity to the direction of movement is measured relative to a textured background, then all subtypes of dyslexia exhibit motion discrimination deficits (12,13).

In many visual areas, including cortical area V1, focal attention, as required for left-right movement discrimination, can enhance a cell's peak response (56). Since perceptual learning is gated by attentional mechanisms (57), and inefficient readers had more perceptual learning following practice on direction discrimination, than found for efficient readers, this suggests that the deficits in attentional focus experienced by inefficient readers result from an information overload, since both parvo and magno neurons signal the brain at the same time, and not from an inability to attend from some other source, as claimed by others (46). Practicing left-right movement discrimination significantly improved direction discrimination by improving the gain (contrast sensitivity) of magno neurons. Improving the gain and reducing the time to complete the task suggests that this type of training improved the timing of magno streams, so that they more readily bracket the activity of linked parvocellular neurons, thereby reducing the information overload.

Training direction discrimination over a wide range of test-background spatial frequency combinations, using stimuli in the center of the working range of the motion pathways enables developing the inhibitory and excitatory networks that are needed to develop the timing asynchrony between magnocellular neurons (setting the gain for direction discrimination) and parvocellular neurons (setting up the background frame of reference and extracting features used for object identification). The brains of post-mortem dyslexics indicate they have immature inhibitory networks (58). Training motion sensitivity to the direction a sine wave grating moves relative to a wide range of background spatial frequencies, providing a textured background frame of reference, and presenting a motion stimulus that is long enough to activate both magnocellular and parvocellular streams, thereby activating inhibitory networks, is the most likely reason that the MTR therapy not only provides rapid diagnosis of inefficient readers (12), but also rapid remediation of reading fluency.

The timing required for the activity of magno neurons to bracket the activity of linked parvo neurons requires both inhibitory and excitatory pathways (43). Developing inhibitory networks would explain why the motion after-effect, when the test pattern appears to oscillate from side to side and not move in one direction, disappears after one month of practicing left-right movement discrimination. It is also likely that inhibitory networks are used to remember and see the correct order in a sequence of patterns, *e.g.* letters in a word, or events that unfold before us. Practicing left-right movement discrimination enables the reader to learn to "break the camouflage," which enables the person to see more distinctly the word being read in the sea of words on the page, and each letter of the word.

Conclusions

These results establish that inefficient readers have immature directionally-selective motion pathways that can be remediated rapidly by practicing direction discrimination between patterns that activate the center of the working range of these motion pathways. This is the first time that a reading therapy has been discovered that remediates both phonological and orthographic reading issues of inefficient readers. Moreover, this reading therapy is over ten times faster than competitive therapies, and can be administered in a group setting, unlike competitive therapies. The timing of the brain's visual efficiency is optimized by practicing left-right movement discrimination, enabling significant improvements in a wide range of reading skills, including reading fluency, with ease and enjoyment. This study demonstrates that learning direction discrimination is linked to learning to read. The MTR therapy, along with reading for at least 15 minutes each day, results in significantly faster and more accurate reading skills, rapidly transitioning young inefficient readers to efficient readers.

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References

1. Cornelissen, P.L., Hansen, P.C., Gilchrist, I.D., Cormack, F., Essex, J., Frankish, C. (1998) "Coherent motion detection and letter position encoding", *Vision Res.* **38**, 2181-2191.
2. Lovegrove, W.J., Bowling, A., Badcock, D. & Blackwood, M. (1980) "Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency", *Science*, **210**, 439-440.

3. Stein, J.F. (1991) ”Visuospatial Sense, Hemispheric Asymmetry and Dyslexia”, In *Vision and Visual Dyslexia*, ed. J.F. Stein, CRC Press, Boston, 181-188.
4. Talcott, J.B., Witton, C. McLean, M.F., Hansen, P.C., Rees, A. & Green, G.G.R. (2000) “Dynamic sensory sensitivity and children’s word decoding skills”, *PNAS*, 97, 2952-2957.
5. Kimura, D. & Archibald, Y. (1974) “Motor functions of the left hemisphere”, *Brain*, **97**, 337-350.
6. Stanley, G. & Hall, R. (1973) “Short-term visual Information processing In dyslexics” *Child Develop.* **44,** 841-844.
7. Tallal, P., Miller, S. & Fitch, R.H. (1993) “Neurobiological basis of speech: a case for the preeminence of temporal processing”, *Ann. N.Y. Acad. Sci*. **682**, 27-47.
8. Atkinson, J. (1991) “Review of human visual development: crowding and dyslexia”, *Vision and Visual Dyslexia*, Ed. J.F. Stein, CRC Press, Boston, 44-57.
9. Griffin, J.R. & Walton, H.N. (1987) *Dyslexia Determination Test*, Los Angeles: Instructional Materials and Equipment Distributors.
10. Stein, J. & Walsh, V. (1997) “To see but not to read; the magnocellular theory of dyslexia”. *TINS*, **20**, 147-152.
11. Stein, J. (2001) “The magnocellular theory of developmental dyslexia”. *Dyslexia*, **7**, 12-36.
12. Lawton, T. (2000) *Methods and Apparatus For Diagnosing and Remediating Reading Disorders*, *United States Patent No. 6,045,515.*
13. Ridder, W.H., Borsting, E., & Banton, T. (2001) “All developmental dyslexic subtypes display an elevated motion coherence threshold”, *Optom. Vis. Sci.* **78**, 510-517.
14. Slaghuis, W.L. & Ryan, J.F. (1999) “Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia”, *Vision Res.* **39**, 651-668.
15. Eden, G.F, VanMeter, J.W., Rumsey, J.M., Maisog, J.M., Woods, R.P. & Zeffiro, T.A. (1996) “Abnormal processing of visual motion in dyslexia revealed by functional brain imaging”, *Nature*, **382**, 66-69.
16. Demb, J.B., Boynton, G.M. & Heeger, D.J. (1998) “Functional magnetic resonance imaging of early visual pathways in dyslexia”, *J. Neurosci.* **18,** 6939-6951
17. Fiorentini, A. & Berardi, N. (1981) “Learning in grating waveform discrimination: specificity for orientation and spatial frequency”, *Vision Res.* **21**, 1149-1158.
18. Ball, K. & Sekuler, R. (1987) “Direction-specific improvement in motion discrimination”, *Vision Res.* **27**, 953-965.
19. Sagi, D, & Tanne, D. (1994) “Perceptual learning: learning to see”, *Curr. Opin. Neurobiol.* **4,** 195-199.
20. Ungerleider, L.G. & Mishkin, M. (1982) “Two cortical visual systems”, in *Analysis of Visual Behavior*, eds. D.J. Ingle, M.A. Goodale, & R.J.W. Mansfield, MIT Press, Boston, pp. 549-586.
21. Thatcher, R. W, Walker, R.A, Giudice, S. (1987) “Human cerebral hemispheres develop at different rates and ages”, *Science*, **236**, 1110-1113.
22. Lawton, T. (1984) “The Effect of Phase Structures on Spatial Phase Discrimination”, *Vision Res.* **24,** 139-148.
23. Torgesen, J.K., Rashotte, C.A., Alexander, A. Alexander, J., & MacPhee, K. (2003) “Progress towards understanding the instructional conditions necessary for remediating reading difficulties in older children”, In B. Foorman (Ed.), *Preventing and Remediating Reading Difficulties:Bringing Science to Scale*. (275-298). Baltimore, MD: York Press.
24. Berninger, V., Nagy, W., Carlisle, J., Thomson, J., Hoffer, D., Abbot, S. & Johnson, C. (2004) “Effective treatment for dyslexics in grades 4 to 6: Behavioral and brain evidence”, In B. Foorman (Ed.), *Preventing and Remediating Reading Disability:Bringing Science to Scale*. (pp 382-417). Timonium, MD: York Press.
25. Livingstone, M.S., Rosen, G.D., Drislane, F.W., & Galaburda, A.M. (1991) “Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia”, *PNAS,* **88**, 7943-7947.
26. Lawton, T. (1989) “Outputs of Paired Gabor Filters Summed Across Background Frame of Reference Predicts Direction of Movement”, *IEEE Trans. Biomed. Eng.* (special issue on neurosystems and neuroengineering), **36,** 130-139.
27. Livingstone, M.S. & Hubel, D.H. (1988) “Segregation of color, form, movement and depth: Anatomy, physiology, and perception”, *Science*, **240**, 740-749.
28. Trachentberg, J.T. & Stryker, M.P. (2001) “Rapid anatomical plasticity of horizontal connections in the developing visual cortex”, *J. Neurosci.* **21**, 3476-3482.
29. Merigan, W.H. & Maunsell, J.H.R. (1993) “How parallel are the primate visual pathways?”, *Ann. Rev. Neurosci.* **16**, 369-402.
30. Legge, G.E. (1978) “Sustained and transient mechanisms in human vision: Temporal and spatial properties”, *Vision Res.* **18**, 69-81.
31. Kaplan, E. & Shapley, R.M.(1986) “The primate retina contains two types of ganglion cells, with high- and low-contrast sensitivity”, *PNAS*, **83**, 2755-2757.

32. Albright, T.D. (1984) “Direction and orientation selectivity of neurons in visual area MT of the macaque” *Neurophysiol.* **52**, 1106-1130.
33. Westheimer, G. (1954) “Eye movement response to a horizontally moving visual stimulus” *Arch. Ophthal.* **52**, 932-941.
34. Carpenter, R.H.S. (2001) “Express saccades: is bimodality a result of the order of stimulus presentation?” *Vision Res.* **41**, 1145-1151.
35. Georgeson, M.A. and Scott-Samuel, N.E. (1999) “Motion contrast: a new metric for direction discrimination” *Vision Res.* **39**, 4393-4402.
36. Rainville, S.J.M., Scott-Samuel, N.E. & Makous, W.L. (2002) “The spatial properties of opponent-motion normalization” *Vision Res.* **42**, 1727-1738.
37. Adelson, E.H. and Bergen, J. (1985) “Spatio-temporal energy models for the perception of motion” *J. Optical Soc Am*, **2**, 284-299.
38. Burr, D.C., Morrone, C. & Maffei, L. (1981) “Intra-cortical inhibition prevents simple cells from responding to textured visual patterns” *Exp. Brain Res.* **43**, 455-458.
39. Zohary, E.S., Celebrini, K.H., Britten, & Newsome, W.T. (1994) “Neuronal plasticity that underlies improvement in perceptual performance” *Science*, **263**, 1289-1292.
40. Zeki, S.M. “Functional organization of a visual area in the posterior bank of the superior temporal sulcus of the rhesus monkey” *J. Physiol. (London)*, **277,** 273-290 (1974).
41. Newsome, W.T. & Pare, E.B. (1988) “A selective impairment of motion perception following lesions of the middle temporal visual area (MT)” *J. Neurosci.* **8**, 2201-2211.
42. Griffin, J.R. (1992) “Genetics of Dyseidetic Dyslexia” *Optom. Vis. Sci***.,** **69**, 148-151.
43. De Valois, R.L, Cottaris, N.P, Mahon, L.E., Elfar, S.D., & Wilson, J.A. (2000) “Spatial and temporal receptive fields of geniculate and cortical cells and directional selectivity” *Vision Res.* **40**, 3685-3702.
44. Yabuta, N.H., Sawatari, A., & Callaway, E.M. (2001) “Two functional channels from primary visual cortex to dorsal visual cortical areas” *Science*, **292**, 297-300.
45. Facoetti, A., Lorusso, M.I., Paganoni, P. (2000) “The spatial distribution visual attention in developmental dyslexia” *Exp Brain Res*., **4**, 531-538.
46. Stuart, G.W., McAnally, K.I., & Castles, A. (2001) “Can contrast sensitivity functions in dyslexia be explained by inattention rather than a magnocellular deficit?” *Vision Res.* **41**, 3205-3211.
47. Trauzettel-Klosinski, Mackeben, M.S., Reinhard, Feucht A, Duerrwaechter U J, & Klosinski, G. (2002) “Pictogram naming in dyslexic and normal children assessed by SLO” *Vision Res*. **42**, 789-799.
48. Williams, M.J., Stuart, G.W., Castles, A., McAnnally, K.I. (2003) “Contrast sensitivity in subgroups of developmental dyslexia” *Vision Res.* **43**, 467-477.
49. Skottun, B.C. (2000) “The magnocellular deficit theory of dyslexia: the evidence from contrast sensitivity” *Vision Res.* **40**, 111-127.
50. Baker, C.L. (1988) “Spatial and temporal frequency selectivity as a basis for velocity preference in cat striate cortex neurons” *Vis. Neurosci.* **4,** 101-113.
51. Pasternak, T. (1987) “Discrimination of differences in speed and flicker rate depends on directionally selective mechanisms” *Vision Res.* **27**, 1881-1890.
52. Thiele, A., Dobkins, K.R. & Albright, T.D. (2000) “Neural correlates of contrast detection at threshold” *Neuron*, **26**, 715-724.50.
53. Levinson, E. & Sekuler, R. (1975) “The independence of channels in human vision, selective for direction of movement” *J. Physiol.* (Lond.) **250**, 347-366.
54. Borsting, E., Ridder, W.H., Dudeck, K., Kelley, C., Matsui, L. Motoyama, J. (1996) “The presence of a magnocellular defect depends on the type of dyslexia” *Vision Res.* **36**, 1047-1053.
55. Lawton, T. (1985) “Spatial Frequency Spectrum of Patterns Changes The Visibility Of Spatial-Phase Differences” *J. Optical Society of America A.*, Feature Issue on Spatial Vision, **2,** 1140-1152.
56. Haenny, P.E. & Schiller, P.H. (1988) “State dependent activity in monkey visual cortex. I. Single cell activity in V1 and V4 on visual tasks” *Exp. Brain Res*. **69**, 225-244.
57. Ahissar, M. & Hochstein, S (1993) “Attentional control of early perceptual learning”, *Proc. Nat. Acad. Sci.* **90**, 5718-5722.
58. Galaburda, A.M., Sherman, G.F., Rosen, G.D., Aboitiz, F. & Geschwind, N. (1985) "Developmental dyslexia: four consecutive cases with cortical anomalies", *Annals of Neurology*, 18, 222-233.