Article

Improving Magnocellular Function in the Dorsal Stream Remediates Reading Deficits

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ABSTRACT

Purpose. This study examined the effects of Direction Discrimination Training (DDT) on reading performance in dyslexics. In particular, the study examined whether increasing stimulus complexity and the amount of training would increase reading fluency more than in previous studies, as well as whether these improvements were sustained over time.

Methods: DDT, using patterns that maximally activate magnocellular neurons, was administered to dyslexic children over the same amount of time (3 months) for twice the frequency each week, using twice as many stimulus complexity levels, as administered in previous studies. A computer-based reading speed task followed DDT to provide reading practice. In addition, the results from the same dyslexics in two previous studies were reanalyzed to determine whether the improvements in reading fluency following DDT in second grade were retained and manifest in third grade.

Results: Contrast sensitivity for direction discrimination increased significantly over that found previously. Reading rates improved 11 fold, in contrast to previous studies of DDT over the same length of time, which found that reading rates improved only 4 fold. Not only did reading fluency improve when dyslexics were trained to discriminate the direction of motion at low contrasts, but spelling, word identification, and comprehension also improved 1-3 grade levels. These improvements persisted over time.

Conclusions: These results suggest that improving the timing and sensitivity of the direction selective cells is linked to improving reading performance. DDT appears to improve magnocellular function in the dorsal stream which may be essential for guiding the attention gateway. The data suggest that it tunes visual neural timing in the dorsal stream, enabling it to guide the ventral stream, improving reading skills, as well as figure/ground discrimination, attention, and processing speed. Our data indicates that this program provides a comprehensive, rapid, and effective regimen for remediating reading problems.

Keywords: contrast sensitivity, cortical plasticity, direction discrimination training, magnocellular, parvocellular, perceptual learning, reading remediation.

Introduction

There is no greater educational problem facing our schools than children who have trouble reading. Reading is the gateway to nearly every other form of academic knowledge. Although estimates vary among researchers, most estimates of the prevalence of reading problems range from 10 to 80%. The most common diagnoses are dyslexia and reading below proficiency. Ten years ago, the prevalence of dyslexia was estimated to be between 5% and 17%.[1] The reading problems encountered in the schools are much worse than may be determined from the percentage of dyslexics. Indeed, nationwide, 67% of the children in 4th grade are reading below proficiency according to the National Assessment of Educational Progress.[2]

Dyslexia is defined as partial alexia in which letters, but not words, may be read, or in which words may not be decoded (word recognition) or encoded (word recall for proper spelling) at normal levels.[3] Dyslexia is a multifaceted learning disability that encompasses both pronunciation-based and visual processing-based issues. Dyslexia can be expressed as inefficient word recognition and orthographic skills when spelling phonetically irregular words, and/or as poor phonological skills (e.g., not being able to report how parts of a word sound) when decoding and encoding unfamiliar words. There are three categories of dyslexia, as introduced by Boder: 1) dyseidetic (trouble with sight-word recognition and spelling phonetically irregular words such as 'laugh' or 'should'), 2) dysphonetic (trouble sounding out words by word attack), and 3) both dysphonetic and dyseidetic.[4]

There are disagreements on the causes of dyslexia, with some attributing it to deficits in phonological processing,[5-9] and others attributing it to deficits in visual processing.[10-18] Here we take the view that the problem is one of temporal processing, or timing, which may be in the auditory domain, the visual domain, or both.

Some children with dyslexia are reported to have visual spatial sequencing deficits, e.g., letters shifting in their position in the word, thereby not being encoded correctly.[10,11,13-18] In addition, dyslexics may have temporal sequencing deficits in either visual[19,20] and/or auditory[8,21] processing, so individual letters or sounds in a word are not decoded correctly. These timing deficits may cause the letters in words and the words on a page to be seen in the wrong sequence or crowded together.[22] Dyslexic readers also show motion discrimination deficits, including an impaired ability to discriminate both the direction[23-30] and the speed[31,32] of moving visual patterns. These spatial and temporal sequencing difficulties are believed by some investigators to result from faulty neural timing.[8,12,15,17,18,21,26,33] In addition, timing deficits in naming speed have been shown to be better predictors of reading problems than deficits in phonological processing.[34]

The Theory that Timing or Magnocellular Deficits Underlie Reading Impairments

The human visual system has predominantly two types of retinal neurons that form two different pathways, the parvocellular, or ventral, pathway (for form discrimination), and the magnocellular, or dorsal pathway (for location and motion processing). The timing deficits that are believed to prevent efficient reading may lie in the linkage between the parvocellular and magnocellular pathways. While not all inefficient readers are dyslexic, this timing deficit is particularly pronounced in those who are.[26,27]

Timing deficits manifest themselves as an impaired ability to either 1) discriminate the direction of change of auditory stimuli, which leads to issues in phonemic awareness,[8,21] or 2) discriminate the direction of motion of moving patterns.[24-30] The deficits in motion discrimination may result from problems in the cortical direction-selectivity network between V1 (primary visual cortex) and MT (Middle Temporal visual area).[24-27] The direction-selectivity network is composed of predominantly magnocellular neurons.[35-38] Magnocellular neurons, which have large axons and dendritic arbors, however, are not sufficient by themselves for direction selectivity.[39] The activity of magnocellular neurons tells the brain where to analyze the activity of the linked parvocellular neurons, which have small axons and dendritic arbors, and are necessary for decoding the edges of the letters in the word being analyzed. Magnocellular neurons, which signal at pattern onset and offset, are excited by low spatial frequency, high temporal frequency, and low contrast patterns, while parvocellular neurons, which analyze the detailed pattern information in the object of interest, are excited by high spatial frequency, low temporal frequency, and high contrast patterns.[8] In analyzing low spatial frequency information, magnocellular neurons provide a global description of a word, e.g. its overall shape and its location; parvocellular neurons provide the local details so that the letters in the word can be deciphered. Parvocellular functioning among dyslexics has been found to be the same as in normal controls.[40,41] On the other hand, magnocellular dysfunction in dyslexics is indicated by high contrast thresholds for direction discrimination, since a normally functioning magnocellular pathway is sensitive to low-contrast patterns.[42]

Magnocellular neurons may also be responsible for detecting the frequency (pitch) and speech amplitude changes that comprise letter sounds in the auditory pathway.[15] Distinguishing different sounds depends on being able to identify these rapid changes in the speech signal.[43] Interestingly, dyslexics are impaired in detecting these rapid changes in speech.[8,43] It is likely that the reason both auditory "motion" and visual

motion discrimination, which are located in different cortical areas, are poor in dyslexics is that their magnocellular neurons are incompletely developed.[15]

In previous studies, dyslexics of all three types mentioned above have been found to have a lowered contrast sensitivity for left-right movement, when movement is judged relative to a textured background.[26-28] The large differences between the direction discrimination Contrast Sensitivity Functions (CSF) for dyslexic and normal readers[25-27] suggest that the direction discrimination network[39] may be immature in dyslexic readers. Some dyslexics have been shown to exhibit deficits in direction discrimination tasks only when patterned background patterns are used.[24-28] Patterned backgrounds, as opposed to featureless backgrounds, require figure/ground discrimination, suggesting that a core deficit in dyslexia is figure/ground discrimination. Some investigators hypothesize that it is the lack of synchronization in timing between magnocellular and parvocellular activation in dyslexics, caused by sluggish magnocellular neurons, that prevents effective pattern analysis and figure-ground discrimination and hence prevents efficient reading.[12,33] Furthermore, it has been suggested that it is the relative timing between magnocellular and parvocellular activations that enables sequential processing to be done effortlessly, i.e., without excessive regressive saccades.[17,18]

Plasticity: Direction Discrimination Training (DDT) Can Ameliorate Magnocellular Deficits

Using stimulus patterns that maximally activate magnocellular neurons in cortical areas V1 and MT in the dorsal stream, several studies have shown that dyslexics who initially had a reduced contrast sensitivity to direction discrimination compared to normal readers improved in both contrast sensitivity and reading speed up to four fold following training on direction discrimination.[24-27] Training auditory "movement" discrimination (fast pitch changes, with short interstimulus intervals (ISI's) has been found to improve phonological processing significantly in dyslexics.[8,21] These studies suggest that sluggish magnocellular neurons in both the auditory and visual systems can be trained, and by improving their timing, reading skills can be enhanced significantly.

Previous studies found that when the difficulty of Direction Discrimination Training (DDT) was increased by using multifrequency backgrounds to increase the complexity of the background pattern,

then the normal observer's contrast sensitivity for direction discrimination improved significantly over previous methods.[44,45] When in addition to single frequency backgrounds, these multifrequency backgrounds were used for DDT with dyslexics, then, after completing equal amounts of training, reading rates increased from two-fold[25] to four-fold.[26] Moreover, the more dyslexics were trained on direction discrimination, the more reading rates improved. [24-27]

The obvious questions that arise include: 1) Will reading rates improve even further with more training and with a greater variety of background patterns, i.e. increasing the levels of background complexity, and 2) Are these improvements in reading skills sustained over time? Examining the data from three additional children will be used to answer the first question, referred to subsequently as the Increased Complexity Study. A reanalysis of two previous studies[25,26] will be used to answer the second question, referred to subsequently as the Follow-Up Analysis. In addition, coached guided reading, saying words with the child immediately following DDT was used to improve reading fluency. This variation was introduced based on the concept that direct practice of the task that needs improvement (reading) immediately after DDT would aid the child by engaging the system that has just been trained.

Methods
Experimental Design

Follow-Up Analysis: The current study sought to assess the effectiveness in improving reading fluency when administering the DDT regimen (described below) over a longer term than had been evaluated previously. Since one class of children participated in one study when they were in second grade[25] and in a second study the subsequent year[26] when they were in third grade, data from these two studies has been reanalyzed and is presented in the Results. The DDT was similar to the Procedures used in this study, the detailed methodology being reported previously.

Increased Complexity Study: Three additional children in elementary school were trained on direction discrimination twice as frequently and with more levels of background complexity than were used for training previously. These children received: 1) more extensive training than previously, (26 replications of the complete set of 20 patterns, as compared to 15 replications)[25,26] and 2) the complexity of the background of the display was increased. Low-

Table 1: Initial and Final Reading Skills for Dyslexics in the *Increased Complexity Study*.

Subject Number	Age (Years)	Reading Grade Level		Dyseidetic Level		Dysphonetic Level		Visual Processing Level		Reading Speed (words/minute)			Number Replications	Number Complexity Levels
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Imp		
1	5	1	2	3	3	4	1	4	1	58	813	14	27	16
2	8	1	2	3	2	6	5	5	1	89	925	10	24	14
3	9	3	4	3	1	5	4	4	2	123	1009	8	27	14

Values for the Dyseidetic and Dysphonetic and Visual Processing Levels correspond to:1: Above Normal, 2: Normal, 3: Borderline, 4: Mild, 5:Moderate, 6: Markedly Below Normal.
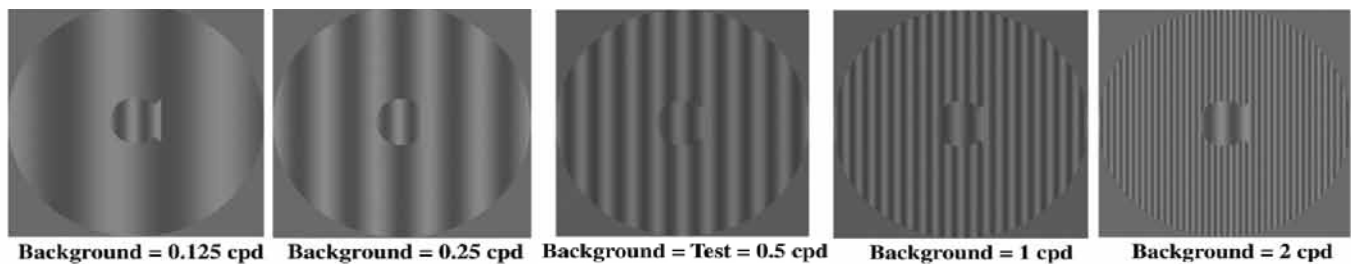

Background = 0.125 cpd   Background = 0.25 cpd   Background = Test = 0.5 cpd   Background = 1 cpd   Background = 2 cpd

Figure 1. *Background patterns of differing difficulty when the "fish shaped" test pattern is 0.5 cycles per degree. The most difficult is when the background is the same as the test, 0.5 cycle per degree.*

complexity (single frequency) backgrounds are used initially until low contrast thresholds for discriminating the direction of movement are reached for a range of different patterns. The next level of complexity is then chosen automatically by the computer, which first increases the background from single to multiple frequencies, then increases background contrast, and finally increases temporal frequency. This increase in complexity involves increasing contrast from 5% to 20%, and temporal frequency from 6.7 cycles per second (Hz) up to 13.3 Hz, which is centered around the child's peak temporal frequency of 10 Hz, so the task is challenging but not too difficult.

Subjects

Follow-Up Analysis: Six children, 4 Hispanic and 2 Caucasian, in one classroom in Santa Monica, CA had DDT in both second grade[25] and third grade.[26] The improvement in their reading skills over these two years is presented in the Results.

Increased Complexity Study: Three children were referred by private therapists for treatment. Their parents reported that these children had been diagnosed with dyslexia by their developmental optometrists and private therapists. Furthermore, all other reading interventions had proven ineffective for resolving their reading issues. These children, who were Caucasian, were aged 5, 8, and 9 years old, and

all three were reading one to two grade levels lower than their actual grade level. These children were borderline dyseidetic, having more severe dysphonetic issues, from markedly below normal to mildly below normal in their ability to sound out words, determined using the Decoding-Encoding Screener for Dyslexia (DESD) dyslexia screener described below. Their initial and final dyseidetic and dysphonetic levels are reported in Table 1 in the Results. In addition, they were all slow readers for their grade level.

Procedures

The DESD (a rapid standardized screener distributed by Western Psychological Services, Los Angeles, CA) was administered at the beginning and end of the DDT to evaluate each child's degree and type of dyslexia. In preparation, each child received a comprehensive and standardized 4-minute video instruction via computer to learn how to complete both the DDT and reading speed tasks. Reading speed and contrast threshold data were automatically recorded by the training programs.

Increased Complexity Study: DDT was administered after school and before doing homework twice a week for 14 weeks. A computer-based reading speed task followed DDT with guided coached reading (the experimenter saying the words just after

Figure 2. *Background patterns of increasing contrast when the "fish shaped" test pattern is 1 cycle per degree and the fundamental frequency of the background is 1 cycle per degree.*

the child and pointing to move the child's eye's to the next word quickly).

Follow-Up Analysis: In both second and third grade, DDT was administered twice a week for 15 weeks, during the school day in the morning before directed reading.

Left-Right Movement (Direction) Discrimination Training (DDT)

The child sat in front of a computer monitor with a display similar to the ones in Figs. 1 and 2. DDT used displays (Fig. 1) comprising a stationary, central, "fish-like" window surrounded by a stationary, vertically oriented sinewave grating. A given trial comprised three frames, each lasting 150 ms, to ensure that a long duration dynamic stimulus was used so the task was easier for dyslexic readers. The amount the test grating moved across space on each frame, the direction (left or right, chosen randomly), was optimal for discriminating the direction of movement.[46] 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 to enable learning the correct direction of motion.

At the start of a session, the test pattern's contrast was set to 5%, to ensure it was in the middle of the magnocellular contrast range.[48] Each time the child correctly identified the direction the fish stripes moved, the contrast of the test grating was lowered until the child made an incorrect response. Following the first incorrect response, a double-staircase procedure[46] was used to estimate the direction discrimination contrast thresholds, which allowed estimating the contrast sensitivity, defined as (1 / {contrast threshold}). Each error increased the test grating contrast by one step. Three correct responses in a row decreased the test grating contrast by one step. The staircase terminated after six reversals, and the mean of the last 3 was

taken to estimate contrast threshold. Using the last 3 of 6 contrast reversals was found previously[46] to provide the most reliable results compared to using larger numbers of contrast reversals. If the last 3 reversals, where the threshold value should be leveling off, contained 4 or more increments in contrast, the threshold was considered too variable to be reliable, and the program automatically provided additional training. This staircase procedure estimated the contrast needed for 79% correct responses, providing the most sensitive, repeatable measurements of contrast sensitivity.[47] The program adaptively changed the display contrast (making the intensity difference, the contrast, between the white and dark bars larger or smaller) in order to keep the child at about 79% correct. This allowed the child to always do well, yet always be challenged to improve. When the test and background spatial frequencies were equal, making the background pattern more similar to that in the fish-like window, the task was also more difficult.

In a given staircase run, the center spatial frequency was either 0.25, 0.5, 1, or 2 cyc/deg, and the surround grating spatial frequency was either equal to the test frequency or 1 or 2 octaves higher or lower than the test frequency. A full training cycle of the direction 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). The stimuli used for training on left-right direction discrimination (see Fig. 1) were previously found to be optimal for discriminating direction of movement at low contrasts.[44-46]

In addition to the simple backgrounds used in the first controlled validation study, more complex backgrounds were used in combinations that have been found to facilitate direction discrimination in normal observers.[26,44,45] The complexity level was increased by increasing the number of sinewave components in the
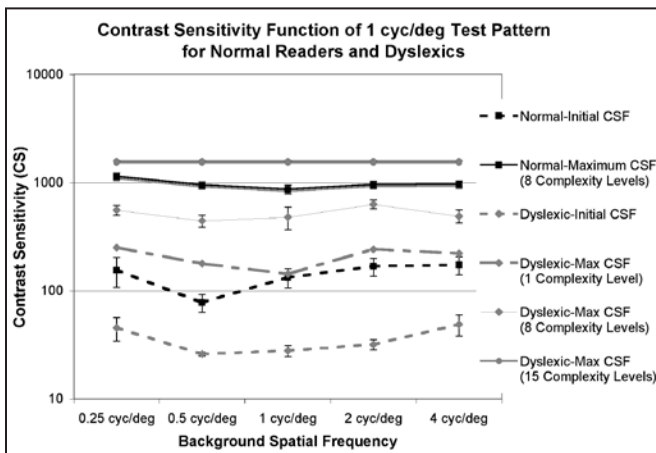
Figure 3. *Mean contrast sensitivity for direction 1 cycle per degree (cyc/deg) test pattern moved relative to backgrounds having different spatial frequencies.*

background from 1 to 3, the background contrast from 5% to 20%, and the pattern's speed of movement, the pattern moved from 6.7 complete spatial cycles in one second, i.e. 6.7 Hz, up to 13.3 Hz, in that order. If the mean contrast thresholds were below 1%, then the level of complexity was automatically increased at the end of a complete set of 20 patterns. The order of presentation was chosen to gradually increase the difficulty of the task.[24,26] Each threshold requires 20-40 trials to complete. A score is given to make the training more game-like. The lower the contrast threshold, the higher is the score. Children typically took about 15-20 minutes to complete one DDT replication, consisting of 20 contrast thresholds.

Computer-Based Reading Speed Task

To assess reading fluency, a procedure called the Reading Rate task was developed to assess reading rate in such a way that the measured rate was in fact limited by a reader's ability to see and process words but not by his or her speaking rate. In this task, continuous, non-repeating lines of text from interesting, easy-to-read stories were presented on the display six words at a time for an interval controlled by a staircase-adjustment procedure. Text at the appropriate reading grade level as determined by the DESD was used to measure reading speeds. Text for children reading at a third grade level was drawn from Stuart Little by E.B. White, for the second grade level was drawn from the Frog and Toad stories by Arnold Lobel, and for the first grade level was drawn from Dr. Seuss stories. The child was told to read the words and speak them to the experimenter. Although the child had a limited time to read the words, they could be spoken both

while they were being displayed and after the words had been removed from the display. Once the words had been read correctly, the research assistant pressed a button that provided positive feedback for 500 ms, in the form of a black plus sign, which appeared just above where the text was presented. The feedback was followed by the display of the next set of six words. If the child made an error, speaking two or more words incorrectly, the research assistant provided a correction, and the same six words were shown again, and a minus appeared. However, the child was now asked to repeat only the words missed in the six words of text. The same phrase was only shown 2 times in a row, so that difficult phrases were not a stumbling block in this task.

Just six words were displayed at a time so that there was no crowding from adjacent words above or below the line being read and at least two saccades were required to read each line of text. The text was rendered using large (0.5 cm wide by 0.5 to 0.75 cm high) white sans-serif letters. The six words of white text were centered in a black window, 1.5 cm high by 14.5 cm wide. The black window was centered in a gray display window of the same mean luminance that was used to test direction discrimination. At the start of the test, the child was seated 57 cm from the display on which the first 6 words of text were presented.

After the initial six words of text were read, staying on the screen until the child was ready to begin this task, the next six words were displayed for 9 seconds, corresponding to a display rate of 40 words per minute. The words were displayed at faster speeds on each presentation until the first incorrect response. A double staircase procedure was used to adjust the presentation time as the child reads the words correctly and incorrectly. Starting from the initial value of 40 words/min, reading rate was increased by 1 step (12%) when five out of six words were read correctly and in the correct order. After an error in reading as judged by the research assistant, the text was repeated once and the child was given a chance to complete the 6 words. The reading rate was then decreased by 1 step. The presentation interval was lengthened (reading speed decreased) until three successive lines of text were read correctly. Then the presentation interval was reduced (reading speed increased). This process continued until 6 reversals in reading speed were obtained. The mean reading-speed threshold was then computed from the mean of the last 3 out of 6
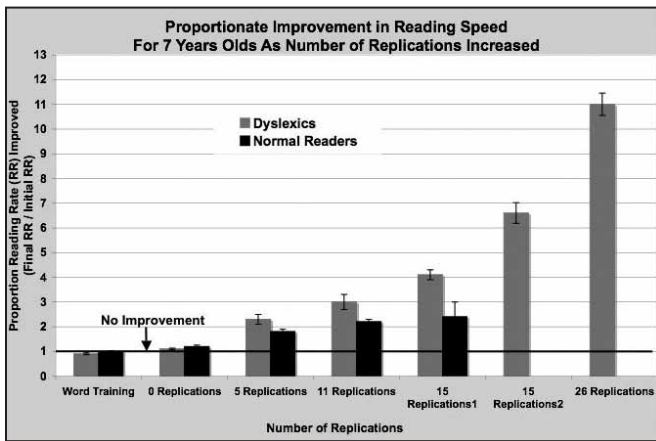
Figure 4. *The more direction discrimination training was used, the more reading rates improved.*
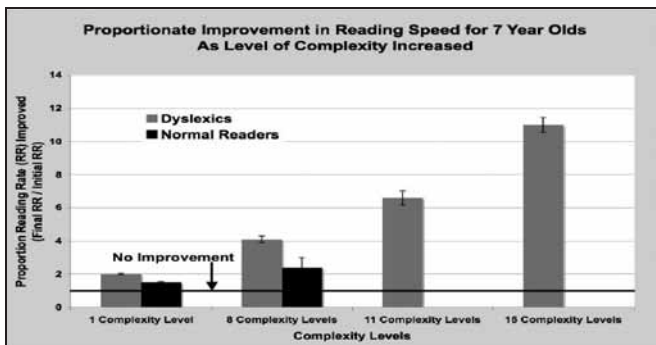

Figure 5. *The more levels of complexity that were used, the more reading rates improved.*

reversals in reading speed. This was repeated with new text to obtain two reading rate estimates. This task took about 3-5 minutes to measure two reading rates. The software kept track of where the child was in the text and never repeated the same text twice (except immediately, if the child mis-read the text).

Results

Increasing Number of Replications and Levels of Complexity for DDT

Data from previous studies with 1 complexity level[25] and 8 complexity levels[26] were replotted in Figure 3 to provide a better comparison with the present data where 15 complexity levels were used. This shows that the more training children had on direction discrimination, the more their direction discrimination CSF increased (Fig. 3). This increase was significant for both for efficient readers, p<0.01 and dyslexics, p<0.001,[26] as also found for dyslexics in the Increased Complexity Study. The improvement for dyslexics was 6 fold with 1 complexity level and 15 replications, 10 fold with 3 complexity levels and 10 replications, 14 fold with 8 complexity levels and 15 replications, and 50 fold with 15 complexity levels and
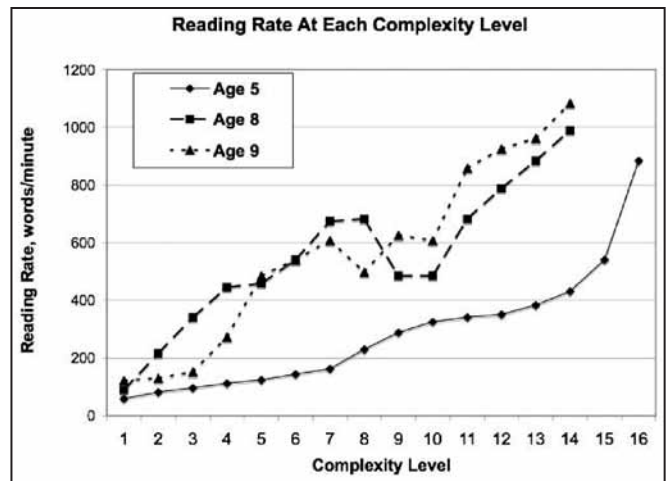

Figure 6. *Reading rate at each complexity level when 26 replications, on average, were completed.*
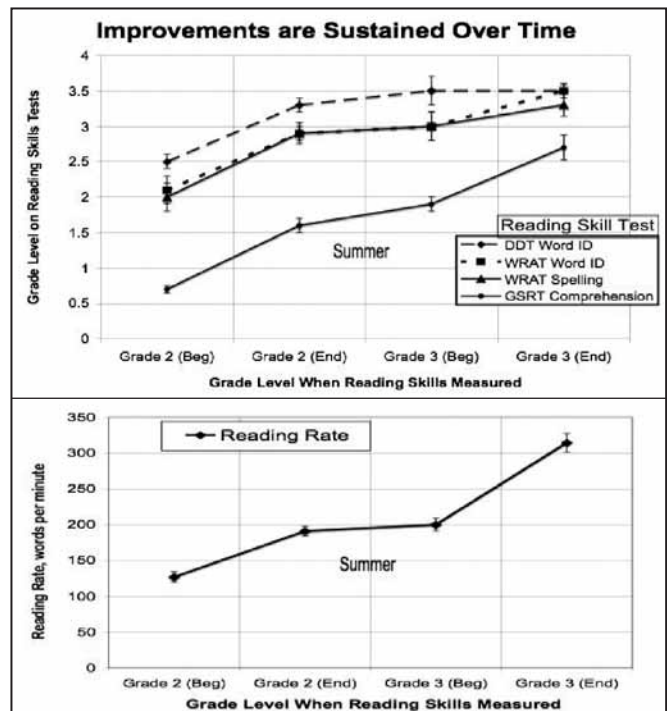

Figure 7. *Reading skills before and after direction discrimination training for same children in second and third grade.*

26 replications. For efficient readers the improvement was 5 fold with 3 complexity levels and 10 replications, and 7 fold with 8 complexity levels and 15 replications. In addition, the direction discrimination contrast sensitivity improved significantly as the number of complexity levels increased, indicating that increasing the background complexity is an effective training stimulus. For both dyslexics and efficient readers, not only did a child's direction discrimination sensitivity improve significantly, but the time to discriminate the direction of movement was reduced significantly (p<0.001),[26] as also found in the Increased Complexity

Study. All children reported that after this training they were able to pay attention in class and when reading, and follow instructions much more easily. These results suggest that activating a wider range of spatial frequency channels, as ensues from using multi-frequency backgrounds at different levels of complexity, provides a more robust and salient frame of reference for direction discrimination.[44,45]

The more often dyslexics and efficient readers were trained on direction discrimination (Figs. 4-7) the more they improved in reading fluency. Data from a previous study[26] has been replotted in Fig. 4, using the number of replications, which was denoted as two sessions of DDT previously. This provided comparison data for both dyslexic and efficient readers in second grade, (Follow-Up Analysis), and with the three children in this study, (Increased Complexity Study), who completed one replication (two sessions) each time they were trained. Increasing the number of replications (Fig. 4) significantly increased reading rates. In addition, for the same number of replications, i.e. 15, increasing the background pattern complexity (Fig. 5) significantly improved reading rates from 4.1 fold[26] (denoted in Fig. 4 as 15-1: 15 replications and 8 levels of complexity) to 6.6 fold as found in this study, (denoted as 15-2: 15 replications and 11 levels of complexity). Dyslexics improved in reading speed 50% after 3 replications, 100% after 5 replications, 300% after 11 replications, 400% after 15 replications,[26] and 1100% (or 11 fold) after 26 replications. Dyslexics improved in reading speed significantly more than did efficient readers in both second and third grade (p < 0.001). Reading rates of the three children in the Increased Complexity Study who did 26 replications and 15 levels of complexity, on average, (Fig. 6) increased as the complexity level increased.

Not only did reading fluency improve when dyslexics were trained to discriminate the direction of motion at low contrasts, but spelling, word identification, and comprehension also improved, as shown in Fig. 7. Moreover, the Follow-Up Analysis found that the improved reading skills obtained at the end of second grade, were sustained over time. They did not decrease over the summer and improved even more after additional DDT was completed during third grade (Fig. 7).

The three dyslexics in the Increased Complexity Study who completed almost twice as many replications as reported previously, (26 replications and 15 levels

of complexity, on average) improved in reading speed 11 fold, on average, following DDT. Reading rates improved at each complexity level, as shown in Fig. 6. Their initial and final reading scores measured by the DESD and the computer–based reading speed are listed in Table 1. The Visual Processing Level (VPL) was obtained by running the diagnostic program for DDT. These values closely correlated with the DESD. These results show that the VPL improved to normal or above normal after 26 replications of DDT for these three children.

The five year old child had been seeing a speech therapist for several years to no avail. When he started DDT, it was difficult to understand what he was saying. After 8 replications of DDT, his speech had improved remarkably. Table 1 shows that his dysphonetic value went from mildly below normal to above normal. This is in large part because he followed DDT with speech therapy. He did not practice spelling, so his dyseidetic score did not improve. On the other hand, the other two children improved one level in visual processing reading skills after 3 months of DDT when practicing spelling on homework after school. Improvements in reading skills only happened if practice on this reading skill followed DDT. Because unpublished research in our lab found that when children did not practice reading after direction discrimination, e.g. during the summer, then reading speeds did not improve, we decided that all studies investigating the effects of DDT on reading fluency would be conducted before directed reading in the school, so the child had plenty of opportunity to practice reading. The more practice on reading, the more that reading skill improved. These results provide more evidence that DDT is opening up the attention gateway to enable sequential processing of letters in words and words in text, as proposed by others.[17] Moreover, these results indicate that DDT improves figure/ground discrimination, speed of processing, word identification, spelling, and reading fluency.

Discussion

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 8 replications of DDT. This increased visible persistence for dyslexics was found previously.[49,50] 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 child is trying to read. This is otherwise known as lateral masking or crowding.[22] By the end of DDT all children reported the words being read popped out and were distinct. These results support the hypothesis that DDT improved figure/ground discrimination, which is developing when a child is learning to read.

A child's visual system is maturing rapidly up until at least the age of 8.[51,52] This is the period when a child is learning to read and there is a great deal of cortical plasticity. Age seven is the middle of the developmental period for learning direction discrimination, the ability to discern the direction that visual patterns move.[24,29] Previous research[17,24-29] is consistent with the hypothesis that children who are inefficient readers have neuronal timing deficits in their visual pathways, as evidenced by poor motion discrimination performance.

DDT is the first known reading intervention that remediates the reading deficits of both phonological (requiring accurate temporal sequencing) and orthographical (requiring accurate spatial sequencing) origin.[26,27] It is hypothesized that phonological language deficits are remediated by tuning the lower cortical visual areas, which in turn, enables tuning the higher language areas, significantly improving the entire spectrum of reading deficits.[26] Interventions that train direction-selectivity to remediate inefficient reading skills[24-27] appear to be much faster and more effective over a wider spectrum of reading deficits than competitive reading interventions that train only phonological processing,[8,9,21] or those that don't vary contrast to train motion discrimination, such as those that measure motion coherence thresholds.[53] Studies are underway to confirm that DDT is faster and more effective for dyslexics than competitive reading interventions.

Direction Discrimination Training (Linked to Reading) Improves Magnocellular Function

DDT, using patterns optimized for activating magnocellular neurons,[24-27,44,45] improved motion sensitivity, which is presumably due to improving the child's magnocellular functioning. Finding that increasing the number of replications and complexity levels increased reading rates even more, provides further evidence that DDT is linked to improving reading. Our working hypothesis in this regard is that a more structured background frame of reference improves the dyslexic reader's ability to discriminate the direction of movement by widening the attention gateway.[26,45] The responses of direction-selective neurons in monkey visual cortex are greatly influenced by attention, and this modulation occurs as early in the cortical hierarchy as the level of MT, showing the influence of attention on motion processing early in the dorsal visual pathway.[54] DDT increased reading speeds 2 to 11 fold, improving reading comprehension, word identification, and spelling from 1 to 3 grade levels. These results suggest that improving the timing and sensitivity of the direction selective cells is linked to improving reading performance. These findings are surprising, since this kind of perceptual learning rarely generalizes to a new task.[55-57]

Dyslexics have an impaired focus of attention,[11,59,60] spending a longer time dwelling on each word, using an increased number of saccades and regressions to read text. This behavior does not seem to be due to a deficit in oculomotor control.[60] The finding that the more training dyslexics completed, the more they improved in reading speed shows direction discrimination results in perceptual learning of reading skills. Since perceptual learning is believed to be gated by attentional mechanisms,[61] this suggests that the deficits in attentional focus experienced by dyslexics[59,60] result from an information overload from timing deficits in the direction-selectivity network,[26] and not from an inability to attend from some other source.[58] Thus one can expect that training on motion discrimination would also benefit attentional mechanisms, as found in this study. Whether improvements in attention are substantiated over time will be investigated using standardized tests of attention in a 4-year study of dyslexic second graders that is currently being conducted in the San Diego Unified School District.

Furthermore, the *Follow-Up Analysis* found that these improvements in reading skills were sustained over time. The longitudinal resilience of DDT is being examined, as well, in the study mentioned in the previous paragraph. This study, funded by the Institute of Educational Sciences at the Department of Education will determine for what types of dyslexia visual and/or auditory timing is most suited for rapid reading remediation, and whether these improvements in reading skills are sustained over time.

By training low-level directionally-selective motion mechanisms using sinewave gratings, it is as though a timing switch was turned on to facilitate learning reading skills. Improving the timing, by
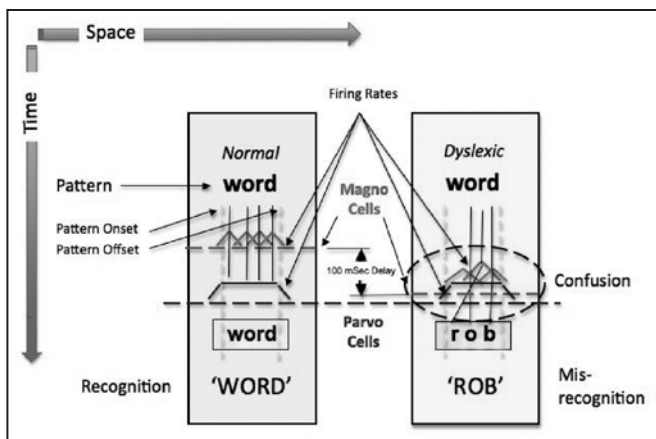
Figure 8. *Schematic of word confusion that results from sluggish timing of magno cells relative to linked parvo cells.*

improving not only the sensitivity for direction discrimination, but also the time to discriminate the direction of movement[26] improved reading fluency when DDT was completed before practice on reading. This training seems to improve dorsal stream function which may be essential for guiding the attention gateway.[26,27,62]

Is Reading Guided by the Dorsal Stream?

Since the magnocellular neurons do not signal in advance of the linked pattern or parvocellular neurons, one possible neurobiological mechanism for the timing deficits in dyslexia is that sluggish magnocellular (motion) neurons found in the Lateral Geniculate Nucleus (LGN) and cortical areas V1 and the Medial Temporal (MT) cortex (posterior portion of the dorsal stream) of dyslexic readers make it difficult to attend in direction discrimination tasks. It is then reasonable to conjecture that the ability of magnocellular neurons to bracket the activity (fire at stimulus onset and offset) of linked parvocellular neurons (those firing as a result of the stimulus pattern details) over time is what has been disrupted in dyslexia, resulting in temporal and spatial sequencing deficits that slow reading speeds. This hypothesis puts forth that magno-parvo activation is like a cell assembly, where the magnocellular information signals the overall shape and form of a word, and where the brain should look to process it. The parvocellular information signals the locations of the edges of the letters so that the high resolution word information can be decoded. Since physiological data demonstrate that magnocellular neurons control the gain of the direction-selectivity network,[39] we hypothesize that the dyslexic reader's more sluggish, immature magnocellular neurons cause a deficit in

attentional focus, preventing the linked parvocellular neurons from isolating and sequentially processing the relevant information needed for reading.[11,17,18,26] Therefore, letters are not decoded correctly, and word confusions, as illustrated in Fig. 8, may occur.

Our working hypothesis is that the magnocellular deficit early in the dorsal visual stream (V1) disrupts all processing later in the dorsal stream (MT -> Medial Superior Temporal cortex (MST)->Lateral Infero-Parietal cortex (LIP)-> Dorsal Lateral PreFrontal Cortex (DLPFC), -> Frontal Eye Fields (FEF), including the development of these processes. In particular, if the magno system gates processing by the parvo system, then this would result in disrupted processing either within a fixation (either left-to-right or temporal disruption of parallel processing), between fixation sequences, or both.[17,18,30,62]

According to our hypothesis, sluggish magnocellular neurons cause a deficit in attentional focus, preventing the linked parvocellular neurons from isolating and processing information essential for reading. Attentional mechanisms controlled by the dorsal visual stream help in serial scanning of the letters in a word, and any deficit in this process will cause a cascade of effects, including impairment in the visual processing of sounds and higher order cognitive processing.[62] Our data suggest that DDT tunes visual neural timing in the dorsal stream, enabling it to guide the ventral stream, improving reading skills, as well as figure/ground discrimination, attention, and processing speed. Figure/ground discrimination is developing at the same time a child is learning to read.

It seems likely that once direction discrimination is improved at low levels of visual processing in V1, then higher levels of processing in the dorsal stream, like MT, where most cells are directionally-selective,[63,64] are also improved. Since cortical feedback from MT amplifies and focuses the activity of neurons in V1 that are used for figure/ground discrimination,[65] 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.

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 and temporal sequencing deficits, as well

as the motion discrimination deficits 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.[24-27]

Claims that Magnocellular Deficits Do Not Underlie Dyslexia

Studies that claim magnocellular deficits do not underlie dyslexia are based on flawed experimental methodology, design, group selection, and/or control groups.[26,62,66,67] For example, Skottum & Skoyles[68] claim flicker discrimination is a good measure of magnocellular neurons in the dorsal stream. Flicker stimuli (e.g. counter-phase gratings) and short duration patterns are not optimal stimuli for activating direction-selective cells.[39,69,70] In addition, counter-phase gratings required twice as much contrast to detect motion,[70,71] compared to sinewave gratings that moved in one direction. Since the assumptions that these authors make are incorrect, as pointed out previously,[66] their conclusions stating that dyslexics do not exhibit a magno deficit have no validity. As described by Stein et al.[67] this problem exists for other studies carried out by Skottum (e.g. Skottum, 2000),[72] as well.

Sperling et al.[73,74] hypothesize that the underlying mechanism in dyslexia is an inability to ignore noise in visual stimuli (the noise exclusion hypothesis). They propose that this inability is not due to a magnocellular deficit, since it shows up in both parvocellular-oriented (static, high frequency Gabor filters) and magnocellular-oriented (counterphase flicker low frequency Gabors) stimuli in their experiments. They purport that if dyslexics have a magno deficit, they should be differentially impaired when discriminating these two different types of stimuli in noise. However, the noise used in their experiments is a flashed white noise stimulus, which activates the magnocellular system,[75] a system that has been implicated in figure-ground discrimination, as stated above. If there is a magnocellular deficit, this would impact both the parvo- and magno-based discriminations because of poor figure/ground discrimination. A better stimulus for their experiments would be comprised of equal test and background spatial frequencies which provide the greatest amount of noise. This is because the test and background patterns are analyzed by neural channels tuned to the same spatial frequencies. Since DDT rapidly removed this deficit,[24-27] these data suggest that

the deficit in noise exclusion found by Sperling et al. is due to the relatively sluggish magnocellular pathway in dyslexics. Hence, the results of Sperling et al.'s experiments are consistent with the view that dyslexia is due to sluggish magnocellular neurons,[76] due to the artifact caused by using flashed white noise in their stimulus presentation. Thus, our data and previous work suggests that there is a stimulus design problem in Sperling et al.'s experiments, since: 1) White noise onset activates the sluggish magnocellular system in their dyslexic subjects; 2) This makes figure/ground discrimination difficult in both conditions; and 3) Amelioration of magnocellular deficits improves figure/ground discrimination, reading speed and other reading skills in dyslexics. The exact mechanism for how the magnocellular deficit impacts reading is an open question for future research.

Conclusions

We believe that the intervention described in this paper, has been shown to provide a comprehensive, rapid, and effective regimen for remediating a wide spectrum of reading deficits. The more training children had on direction discrimination and the more complexity levels that were used, the more reading rates improved. Moreover, these improvements appear to be sustained over time. The data suggest that DDT tunes visual neural timing in the dorsal stream, enabling it to guide the ventral stream, improving reading skills, including reading speed, comprehension, spelling and word identification, as well as figure/ground discrimination, attention, and processing speed. Furthermore, the studies reported and referenced here provide evidence that DDT improves magnocellular function in the dorsal stream, which may be essential for guiding the attention gateway.

Acknowledgements

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G.N. Getman Award: Leonard J. Press, OD, FCOVD

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OVD Journal 2010 Article of the Year: *"Diagnosing Extrocular Muscle Dysfuntion in Clinic: Comparing Computerized Hess Analysis, Park's 3-Step Test and Novel 3-Step Test"*
Patrick Quaid BSc(Hons)Optom, MCOptom, PhD

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