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Reading, Color, and Coherent Motion

Teresa Narayan
University of Missouri-St. Louis, anjali001@gmail.com

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Teresa E. Narayan
O.D., Doctor of Optometry, University of Missouri – St. Louis, 2009
B.A., Biology, Washington University in St. Louis, 2004

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<u>Advisory Committee</u>
Carol K. Peck, Ph.D.
Chairperson

Carl J. Bassi, Ph.D.

Ralph P. Garzia, O.D.

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Abstract

Dyslexia is surrounded by much uncertainty over its cause and its treatment. While many view dyslexia as a purely phonological deficit, some have proposed a visual deficit as a cause in at least some poor readers. Several treatments have been have used to increase visual processing as a means of overcoming such visual deficits. Using a blue colored filter to increase magnocellular processing has seen the most successful outcomes. Tests of coherent motion under different background color conditions were completed on a group of 16 highly educated subjects who also underwent several tests of reading ability. There were no significant differences between the motion thresholds taken under the different color conditions and the motion thresholds did not correlate with any reading measure. However the difference between the white baseline coherent motion threshold and the low contrast gray threshold significantly correlated with several of the reading measures, indicating that poorer readers gained the most increase in motion sensitivity when using a low contrast gray background. This suggests that benefits seen from using colored filters may be due to the reduction in contrast rather than the effect of color. More research needs to be done on the effect of color on both the magnocellular pathway and on reading performance.

Background

Definitions

The causes of dyslexia have been greatly debated and a definitive etiology is still unconfirmed. In fact even the definition is varied depending on the source. The simplest definition generally describes dyslexia as an unexpected difficulty in reading (Shaywitz et al, 2008). The term “unexpected” used in that description implies that dyslexic readers are only categorized as such if their reading fluency is lower than expected with a normal level of intelligence, motivation, reading instruction, experience and all other faculties (Shaywitz et al, 1998). The International Dyslexic Association offers a more specific definition detailing dyslexia as language based learning disability with a neurological origin that comes with a “cluster of symptoms, which result in people having difficulties with specific language skills, particularly reading.” (The IDA, 2010). It goes on to say that people with dyslexia often have trouble with other aspects of language such as spelling, writing, and pronouncing words. Also important to note is that the International Dyslexia Association defines dyslexia as a lifelong condition typically caused by a phonological deficit but states that the impact can vary greatly during different stages of a person’s life. A third definition is the “research” definition detailed by the National Institute for Neurological Disorders and Strokes (NINDS), a division of the National Institute of Health. This is similar to the International Dyslexia Association’s definition and the definition includes mention of a brain-based learning disability that impairs the ability to read (NINDS, 2010). It does not lay specific blame on a phonological deficit as the IDA’s definition does, although the NINDS definition does say that a common characteristic of dyslexics is difficulty with phonological processing among other symptoms including difficulty with spelling and rapid visual-verbal response. Interestingly, the NINDS definition mentions that dyslexia can be inherited and that there are several studies that identify genes that predispose one to developing dyslexia.

The main difference in these definitions, and the reason for much of the controversy surrounding the term, lies in describing the underlying cause and mechanism.

This is likely due to the fact that most definitions arose before a mechanism was clearly understood and so many are instead operational definitions which list the characteristics of the condition but not the cause. The simple definition makes no attempt to explain the cause of dyslexia, instead just stating that the reading difficulties are unexpected given the individual's profile. The International Dyslexia Association definition specifically mentions a neurological problem, indicating that there is a measurable brain dysfunction in dyslexics, and also says that this dysfunction typically manifests itself in a phonological deficit. The National Institute of Neurological Disorders and Strokes definition includes a description of a neurological dysfunction and mentions a genetic component. However it does not rely on a phonological deficit as the cause and chooses to just list several common characteristics of dyslexia.

Phonological and Visual Components

The difficulty in describing the underlying mechanism of dyslexia stems from the fact that the disorder varies from person to person. There likely is not just one cause of dyslexia; rather several different problems that can manifest themselves as reading difficulties which ultimately end up under the dyslexia umbrella. One large point of contention is the visual versus verbal component of dyslexia. As stated in the International Dyslexia Association definition, in most people, symptoms are caused by a phonological deficit, leaving no mention of a visual problem. However studies have shown approximately 75% of reading difficulties involve a visual deficit (Lovegrove et al, 1986) and this number is backed up by significant psychophysical, electrophysiologic, and anatomical evidence that points to visual deficits in dyslexics. This is not to say that those 75% do not also have a concurrent phonological deficit; on the contrary, many of them likely do. Rather than considering dyslexia as a phonological problem or a visual problem, it is more likely that it involves both components. A study testing both visual processing through motion detection and phonological processing via a spoonerism task showed that both were individually correlated with single word reading (Cornelissen et al, 1998). Testing for sensitivity to both auditory and visual dynamic stimuli revealed that visual motion sensitivity explained variance in orthographic skill but not phonological skill and that auditory frequency modulation sensitivity correlated with phonological skill but not orthographic skill. Again, these results indicate that both auditory and visual processes are important to reading and that both are good predictors for literary skills (Talcott et al, 2000; Talcott et al 2002). Another study showed that several visual motor functions, including fixation stability, vergence amplitudes, and smooth pursuits, were decreased even in those dyslexics who had been shown to have a phonological deficit (Eden et al, 1994). Overall, therefore, substantial evidence indicates that a visual component in dyslexia cannot be ignored. In order to determine proper and effective treatments, attention must be paid to the specific nature of these visual deficits.

Visual Deficit Theories

Most current theories on visual deficits that play a role in reading disabilities involve pre-attentive pathways which occur before later stages of vision such as perceptual processing. There are two visual pathways involved in these theories. The magnocellular pathway (also known as the transient pathway), is named for the magnocellular ganglion cells in the dorsal lateral geniculate nucleus and cells with large receptive fields. These cells are tuned for low spatial frequencies, luminance detection, and motion sensitivity and the responses are short and fleeting. The other visual pathway used in reading is known as the parvocellular or sustained pathway. Parvocellular cells are tuned for high spatial frequencies and therefore allow for detection of details (such as letters in reading) and color vision and they have longer responses. One other important difference between the two pathways is that the magnocellular signals reach the visual cortex 7 to 10 ms faster than parvocellular signals (Maunsell and Gibson, 1992). Experiments investigating visual masking effects have also shown that the magnocellular pathway is faster with short wavelength stimuli and the parvocellular pathway is faster with long wavelengths (Williams et al, 1991).

Visual deficit theories of dyslexia usually involve a slowed and less robust magnocellular pathway. Visual evoked potentials recorded from normal individuals and dyslexic individuals have shown that dyslexics have longer latencies when viewing targets designed to activate the magnocellular system (Livingstone et al, 1991; Lehmkuhle et al, 1993). Anatomical studies have also demonstrated that dyslexics have smaller magnocellular cells in the dorsal lateral geniculate nucleus than normal readers (Livingstone et al, 1991). A magnocellular deficit is also indicated by several psychophysical studies which show that poor readers have abnormally low coherent motion sensitivities (Cornelissen et al, 1995; Solan et al, 2003; Sperling et al, 2003). Coherent motion sensitivity refers to the ability to discriminate between dots that are moving randomly and dots that are moving together in one direction. Thus it measures a threshold for motion, whereby higher threshold (more dots need to be moving together in order to detect the coherence) equals a lower sensitivity. These studies have shown that poor readers have significantly higher coherent motion thresholds (and therefore lower sensitivities) than normal readers, suggesting that a depressed magnocellular system may be present in some poor readers. Studies have also shown that troubled readers have significantly more difficulty on tasks with a high amount of magnocellular demand. One such study tested performance on single word reading, reading with a moving box to guide eye movements, and free sentence reading (Williams et al, 1992). Dyslexic readers performed much worse on the last task but there were no significant performance differences across the tasks for normal readers. This shows that increased magnocellular demand causes a decrease in performance for disabled readers but not for normal readers who presumably have normal magnocellular pathway function.

While most visual deficit theories involve a magnocellular deficit, the mechanism of how this deficit affects reading is under debate. It has been speculated that accurate timing of eye movements during reading may be key. During reading the eyes makes saccades to go from point to point with a fixation and cognitive processing between each saccade. Fixations, during which the eyes are stationary, are dominated by the parvocellular pathway because of the need to discriminate fine details of the letters in print. Saccades, during which the eyes are programmed and moved to the next fixation point, are controlled by the magnocellular pathway which is sensitive to motion. Disruption of the timing between the two visual pathways may cause difficulty in reading efficiently. One theory suggests that the magnocellular pathway suppresses the parvocellular pathway during the saccades so that vision is not blurred during reading (Breitmeyer, 1980; Edwards et al, 1996). This system would prevent the parvocellular pathway from trying to decode the letters while the eyes are still moving. A slowed magnocellular system would break the well-timed coordination of the magnocellular and parvocellular pathways that is necessary to efficient reading. Such a timing mismatch may be able to explain some common dyslexic complaints that involve jumping of words around the page. If the magnocellular system is working at a slower rate than the parvocellular system, it would still be active during fixations and that could create that sensation of moving words.

Another magnocellular deficit theory proposes that both the magnocellular and the parvocellular pathways are active during decoding of text while reading (Chase, 1996). The magnocellular pathway, which is tuned for lower spatial frequencies, relays information about the global pattern and shape and the parvocellular pathway, which is sensitive to higher spatial frequencies, fills in the details. It has already been mentioned that the magnocellular pathway is faster than the parvocellular pathway and it has also been shown that low spatial frequencies take 60-80 milliseconds to process whereas high spatial frequencies take 150-200 milliseconds to process (Legge, 1978). Therefore the visual system first gets diffuse global information from the magnocellular cells and then the parvocellular cells adds in finer details during a later stage of processing. One study has shown that the magnocellular pathway plays an important role in letter position encoding (Cornelissen et al, 1998) and another one showed that the magnocellular pathway is involved in the identification of flanked letters (Omtzigt et al, 2002), both which suggest that early processing can be done without the parvocellular pathway. Chase suggests that information from the magnocellular pathway alone may be used for orthographic processing which is the ability to derive information from written language. Information from the parvocellular pathway then is only necessary if the orthographic system cannot make an identification.

Colored Filters

Both of these visual deficit theories involve a less robust magnocellular system and many proposed treatments try to restore the balance between magnocellular and parvocellular pathways by using colored filters and lenses (for review see: Whiteley and Smith, 2001). This adds to the controversy surrounding dyslexia in general because of the many varied points of view regarding the usefulness of colored filters. Many studies have used different colors of filters with varying degrees of success. The use of colored filters in treating reading disabilities was popularized by educational psychologist Helen Irlen and her description of scotopic sensitivity syndrome which has many of the same symptoms that dyslexic readers often report.

Some studies claim that the color of filter used must be specific to each individual reader and that such filters can subjectively and objectively improve reading performance (Irlen, 1994; Wilkins et al, 1992; Wilkins et al, 1994; Wilkins et al, 2005). One study let readers choose their filter and showed that regular filter use (independent of the one chosen) can increase the reading rate and saccadic function if the readers had previous visual complaints (Northway, 2003). Another study proposed that yellow filters should have the biggest effect on boosting both magnocellular pathway function and reading performance but the study used different subjects for the two groups (with and without filters), so individual performance increase was not assessed (Ray et al, 2005). There has also been some debate about whether filters work just by reducing contrast since their function is to remove wavelengths which thereby reduces luminance. Several studies have investigated the role of contrast sensitivity in dyslexic readers with some showing that dyslexic readers have decreased contrast sensitivity (Spafford et al, 1995; Pammer et al, 2001) and one showing that there is no difference in contrast sensitivity between normal and dyslexic readers (Cornelissen et al, 1995). However, most studies which have shown a significant objective increase in reading skill have used a blue filter.

And the evidence which shows the effectiveness of blue filters use in the management of dyslexia has been mounting. Blue filters have been shown to significantly increase reading comprehension in those with a reading disability (Solan et al, 1997; Iovino et al, 1998). A study designed to test the effect of filters on tasks with differing magnocellular involvement showed that disabled readers had significantly better comprehension with a blue filter on the task having the most magnocellular pathway involvement (Williams et al, 1992). In addition, the results showed that red filters decreased comprehension for both normal and disabled readers on all tasks, regardless of magnocellular involvement. Blue filters have also been reported to significantly improve eye movement efficiency during reading for disabled readers by reducing the number of fixations and regressions (Solan et al, 1997).

Again there are multiple theories which try to explain why blue filters are the most successful. As mentioned before, the magnocellular and parvocellular pathways differ in processing speed depending on the wavelength of the stimuli and the magnocellular pathway is faster with short wavelengths while the parvocellular pathway is faster with long wavelengths (Williams et al, 1991). Therefore, some propose that blue filters hinder the parvocellular response in order to restore timing between the two pathways involved in reading (Whiteley and Smith, 2001). This is explained by examining the composition of cones in predominately parvocellular areas on the retina. There are significantly fewer short wavelength sensitive cones in the central area of the retina where the parvocellular pathway dominates. The short wavelength cones would predominately be used when viewing through a blue filter, and since there are less of them, the parvocellular processing time would be increased allowing the magnocellular pathway to catch up.

However, most evidence points to the idea that blue filters boost the magnocellular response, by either enhancing sensitivity by adding short wavelengths or by removing inhibition by filtering out long wavelengths. Magnocellular receptive fields have predominantly long wavelength sensitive inhibitory surrounds (de Monasterio, 1978). Recordings from magnocellular ganglion cell neurons corroborated this idea by showing that the majority have a dominant L-cone input for the surround-field (Reid and Shapley, 1992). These findings suggest that the removal of long wavelengths (reds) reduces inhibition of the magnocellular pathway. One study found no effect from blue light on the magnocellular system and found a small but measurable depression in magnocellular activity under red light conditions (Pammer and Lovegrove, 2001). A study by Chase et al. (2003) also attempted to distinguish between red and blue effects by using different light combinations. Normal readers were required to read out loud from several different passages. It was found that significantly more naming errors were made when readers read a passage with a red-green light combination than with a blue-green light combination. It was also shown that when they used a red-blue-green combination, reading was less accurate than when just a blue-green combination was used. In addition, there was no significant accuracy difference when using a red-green combination versus a red-blue-green combination. Since a decrease in accuracy was seen when red light was used, but an increase in accuracy was not seen with blue light, the conclusion is that the effect was not due to increased short wavelengths but rather due to decreased long wavelengths. This again corroborates the theory that the magnocellular pathway is depressed by long wavelengths. These findings form the basis of my experiment.

This experiment was designed to test the effect of different colored backgrounds on coherent motion sensitivity thresholds. While many studies have tested for coherent motion and its relation to magnocellular and reading function (Cornelissen et al, 1995; Cornelissen et al, 1998; Talcott et al, 2000; Talcott et al, 2002; Solan et al, 2003; Sperling et al, 2003) and many studies have investigated the effect of color on other measures of magnocellular and reading function (Williams et al, 1992; Solan et al, 1997; Solan et al, 1998; Iovino et al, 1998; Pammer and Lovegrove, 2001; Northway 2003; Chase et al, 2003; Dain, 2008), none to date have combined the ideas and tested the effect of color and contrast on coherent motion sensitivity. The experiment is also designed to relate coherent motion performance to reading ability.

Two different measures of reading were first completed to assess the subject's reading skill. The first measure of reading was taken from the Woodcock Johnson III Tests of Achievement. This test battery contains 22 tests and 8 clusters. The Woodcock - Johnson III Broad Reading Cluster was used to give an overall view of the subject's reading ability. It is composed of three tests. The cluster of tests is designed to test several aspects of reading. The first test was Letter Word Identification. This requires the subject to identify single words, thereby testing phonological and orthographic skill without any eye movements required. The next test was Reading Fluency. This involves reading short sentences and answering whether they are true or false. This test is timed and therefore is a measure of reading speed but the true/false nature of the statements incorporates a measure of reading comprehension as well. The last test was Passage

Comprehension. This requires the subject to read a paragraph with a missing word and then fill in the blank with an appropriate suggestion using a standard cloze procedure. This test involves elements of Letter Word Identification and Reading Fluency since it requires word identification but also necessitates eye movements and reading comprehension. The second measure of reading ability was the Visagraph II. A goggle-like apparatus is placed over the subject's eyes to measure eye movements made while reading a short paragraph. The apparatus tracks the subject's eyes as they make fixations and saccades and records the time spent at each fixation point. A short true/false quiz is given at the end to ensure that the subject was reading the paragraph with the intent of comprehension rather than just maximizing speed.

After the reading measures, the subjects were tested for their coherent motion sensitivities under differing background color conditions. Coherent motion tasks, which test a participant's ability to detect the direction of motion of moving dots in a noisy background, are good estimates of magnocellular function because the magnocellular pathway is responsible for motion detection. Based on previously mentioned research stating that long wavelengths inhibit the magnocellular pathway, the colored backgrounds for the coherent motion tasks were designed to investigate this point further. The participants were tested under seven different backgrounds: white, low and high contrast red, low and high contrast blue, and low and high contrast neutral gray. Coherent motion tasks are typically done with a black background and white moving dots but to more closely resemble a reading situation, a white background with black moving dots (analogous to a white page with black type) was used. Red and blue backgrounds were included since red has been shown to depress magnocellular function and blue has been used to increase reading ability (presumably by increasing magnocellular function). Since research has shown that poor readers can have different contrast sensitivities than good readers, the gray color conditions were included in order to determine whether any effects of background on motion sensitivity were caused by the long wavelengths or by the reduced luminance (or both) (Cornelissen et al, 1995; Spafford et al, 1995; Pammer and Lovegrove, 2001). This is also why high and low contrast conditions for each color were included. The high and low conditions also serve to see if increasing color intensity has an effect on performance. An analysis of variance will be calculated for the coherent motion thresholds in each color condition to determine if there is an overall effect of color on coherent motion sensitivity. Correlations for the coherent motion thresholds and the different reading measures will also be calculated to see if the effect of a colored background differs depending on reading ability and eye movement efficiency.

A screening procedure is included to ensure that variables such as decreased vision or color deficiencies are minimized. The Woodcock Johnson III Broad Reading cluster, the Visagraph II measurements, and the coherent motion tasks were then used to collect the data for analysis.

Methods

Initial Screening

All participants were required to have had a recent comprehensive eye examination at the University of Missouri – St. Louis College of Optometry. The results of these examinations were used to eliminate any potential subjects with visual conditions which would interfere with testing. Exclusion criteria included vision that was not correctable to a Snellen acuity of 20/20 at 20 feet and 20/20 at 40 cm, restricted ocular motility and abnormal binocular vision. There were 16 subjects (12 females, 4 males) and inclusion criteria required that subjects were current students at the University of Missouri – St. Louis College of Optometry (≥ grade 18). The average age of the subjects was 24.5 years with a standard deviation of 1.5 years.

Lanthony's desaturated D-15 Color Test

This test is used to exclude any subjects with a color deficiency. The desaturated nature of the colors makes this test very sensitive in finding both congenital and subtle acquired color deficiencies. Subjects were seated at a table with a Macbeth lamp to complete Lanthony's desaturated D-15 test. The color caps were shuffled and placed in front of the subject and instructions were given to choose the cap nearest to the color of the fixed test cap and place it in the second position. A cap nearest to the color of the second cap was then to be placed in the third position and so on until all caps are used. The subject was given a chance to make any changes to the order of the caps and then the test was scored. The test was administered and scored according to standard guidelines.

More than one ordering error indicating a color deficiency led to exclusion from the rest of the study.

Woodcock Johnson III Reading Cluster

All subjects completed the Reading Cluster from the Woodcock Johnson III Tests of Achievement which has appropriate levels of difficulty for the age and grade level of the subjects. This cluster included three tests: Letter Word Recognition, Reading Fluency, and Passage Comprehension. Performance on each test was recorded according to standard procedure.

Letter Word Recognition required the subject to simply read the words from the test aloud. The test was started at the level indicated by the subject's age and progressed forward unless the subject got an incorrect answer within the first six words. In such a case, the previous sections would be tested until the subject got six correct answers in a row before proceeding forward. Recognition and pronunciation of the word was scored according to the guidelines. In accordance with the testing guidelines, the test was stopped if the subject got six incorrect answers in a row. The test was not timed.

Reading Fluency required the subject to read short sentences and answer true or false for each one by circling the chosen response. The subject was instructed to work quickly but accurately and was stopped after three minutes. If the subject finished before three minutes, the time to complete the test was recorded and factored into the final scoring according to the scoring guidelines.

Passage Comprehension required the subject to read a short paragraph with a word missing and chose a word to fit the blank. The subject could read aloud if desired and the test was not timed. The test was started at the level indicated by the subject's age and progressed forward unless the subject got an incorrect answer within the first six paragraphs. In such a case, the previous sections would be tested until the subject got six correct answers in a row before proceeding forward. Multiple answers were accepted and the subject was prompted to give another answer in certain cases as indicated by the scoring guidelines. The test was stopped if the subject got six incorrect answers in a row.

Once the three tests were evaluated for number of errors, the information was scored by a computer program which resulted in three individual standard test scores and a final broad reading cluster standard score. The mean standard score is 100 with a standard deviation of 15.

Visagraph II

The subjects were seated in front of the test booklet and the Visagraph II goggles were put over their habitual prescription. The apparatus was adjusted for the subject's pupillary distance. A 100 word paragraph in the level 10 series, the highest series for grades 10 and above, was chosen and the subjects were instructed to read the paragraph silently or aloud. After reading the paragraph, a ten question true or false reading comprehension quiz was completed. Scores considered for the purposes of this experiment were number of fixations, number of regressions, and fixation duration which are measured directly from the device. Number of fixations refers to the number of times that a subject's eyes paused while reading the passage. Fixation duration is the average length of time that the eyes remained stationary during a fixation. Regressions refer to the number of times the eyes make a backwards movement (right to left). For all these measures, lower numbers mean greater eye movement efficiency during reading. The normal number of fixations for grade 18 (the highest grade available) is 44. The normal length for fixation duration for grade 18 is 0.22 seconds. The normal number of regressions for grade 18 is 2.

Coherent Motion

The subjects were seated 60 cm in front of an EIZO monitor with ambient room lighting. A chin rest was used to stabilize head movements. The Vision Works 3.0 program by Vision Research Graphics was configured to show two random dot kinetograms side by side on the computer monitor. Each kinetogram had a height of 120 mm (11.286 deg) and a width of 93 mm (8.638 deg). The kinetograms each contained 1056 dots with a 2 mm height and 2 mm width (0.024 deg) at a density of 12 dots/cm^2. The dots were moving at a velocity of 26.9 mm/sec (2.5 deg/sec) and they were refreshed every 50 frames (.9021 sec) to prevent tracking of individual dots. These parameters were obtained from other studies using coherent motion as a measure of magnocellular function (Cornelissen et al, 1995; Cornelissen et al, 1998; and Solan et al, 2003). Given that there has been no research to date on coherent motion thresholds with colored background, the other parameters such as patch size, dot size, and speed of motion were kept the same as in studies which showed a definitive decrease in coherent motion thresholds for disabled readers when compared to normal readers (Cornelissen, 1994). The two kinetograms were displayed side by side with one having 100% of the dots moving randomly and the other having a percentage of the dots moving randomly and a percentage of the dots moving coherently together, either to the left or to the right. Based on a two alternative forced choice procedure, the program asked the subject to choose which of the two kinetograms contained the coherently moving dots by pressing a key on the keyboard. The participants were first allowed to adjust to the room conditions and have several practice sessions. Once the subject achieved two successive trials with coherent motion thresholds within 5%, the experimental sessions began.

Each trial required the subjects to choose which of the two displayed kinetograms contained coherently moving dots, with the percent of coherently moving dots decreasing with each correct choice and increasing with each incorrect choice according to a 2 up/ 1 down staircase method using 3 db and 1.5 dB steps where dB=10 $\log k^2$ with k = % coherence. The threshold was determined from the last 6 of 8 total reversals (threshold determination methods were designed from protocols used in Cornelissen et al, 1995; Cornelissen et al, 1998; and Solan et al, 2003). The experimental session consisted of seven different conditions containing backgrounds of varying red, blue, and green gun outputs. The different color conditions had the following background colors: white, high contrast blue, high contrast red, high contrast gray, low contrast blue low, low contrast red, and low contrast gray. The white background had equal output from all three guns (red, blue, and green) with a luminance of 84.1 cd/m^2 as measured with a spectrophotometer. The high contrast blue background had only blue gun output and no red or green gun output and a luminance of 10.3 cd/m^2. The high contrast red background had only red gun output and no blue or green gun output and a luminance of 10.3 cd/m^2. The high contrast gray background had equal output from all three guns (red, blue, and green) and a luminance of 10.4 cd/m^2. The low contrast blue background had only blue gun output and no red or green gun output and a luminance of 6.7 cd/m^2. The low contrast red background had only red gun output and no blue or green gun output and a luminance of 6.62 cd/m^2. The low contrast gray background had equal output from all three guns (red, blue, and green) and a luminance of 6.78 cd/m^2 (see Figure 1 for luminance summary). Black dots with a luminance of 1 cd/m^2 were used throughout all the color conditions. The Weber contrast, which is appropriate for small features on a uniform background, was calculated for each condition. The Weber contrast for the backgrounds with black dots was as follows: white -98.8%, high contrast blue -90.3%, high contrast red -90.3%, high contrast gray 90.3%, low contrast blue -85.1%, low contrast red -84.9%, and low contrast gray -85.3%.

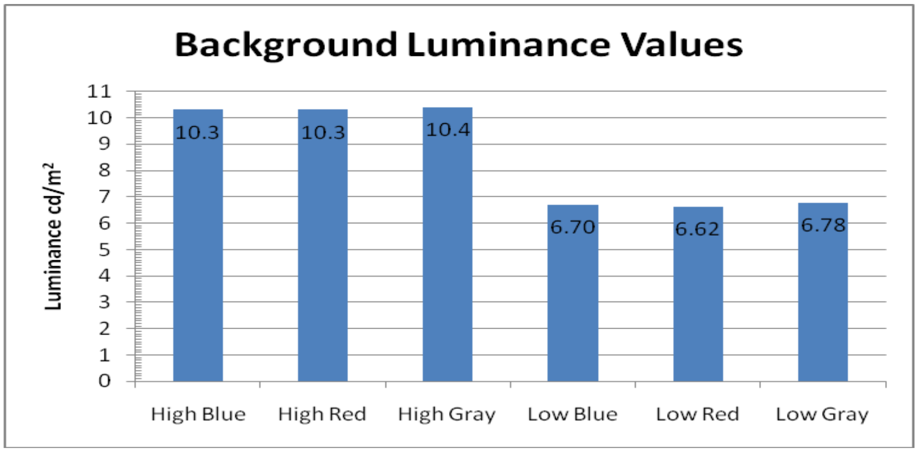

Figure 1: Background Luminance Values

Each color condition was repeated three times, for a total of 21 trials. The order of the presentation of the color conditions was randomized and a coherent motion threshold value based on percentage of coherently moving dots using was determined for each trial.

Results

Woodcock Johnson III Results

The mean standard score for all the subjects on Letter Word Identification was 104.44 with a standard deviation of 10.78. The mean standard score for all the subjects on Reading Fluency was 106.44 with a standard deviation of 16.21. The mean standard score for all the subjects on Passage Comprehension was 104.94 with a standard deviation of 14.15. The mean standard score for the total Broad Reading cluster score as determined by the Woodcock Johnson III version 2.0 scoring program was 108.63 with a standard deviation of 16.60 (see Table 1 for summary). The mean standard score for all the subjects for all three tests and for the broad reading score was above the 100 standard score mean indicating that the subjects as a group had better than average reading skills when compared to the general population (see Figure 2). This result was expected since the subjects are highly educated and they were currently enrolled in a graduate program indicating their proficiency in school and presumably in reading.

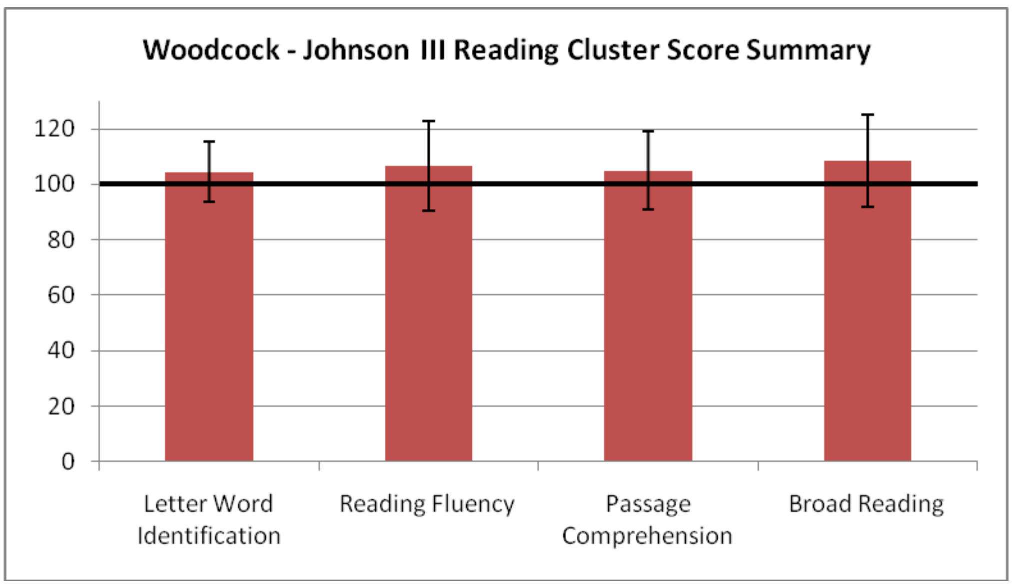

Figure 2: Woodcock – Johnson III Reading Cluster Score Summary

In order to assess the relationship between the different reading tests, Pearson correlation coefficients between the different tests were calculated (see Table 2). Significant ($p<0.05$) positive correlations were found between individual reading scores when compared to the broad reading cluster score. This is expected since the broad reading score is calculated from the individual reading scores. Letter Word Identification is significantly correlated (.525, $p = .037$) with Passage Comprehension. This logically makes sense because Letter Word Identification is measuring the subject's ability to identify and decode words and Passage Comprehension is measuring the ability to understand a paragraph and fill in the missing word. It is interesting to note, though, that neither Letter Word Identification nor Passage Comprehension is correlated with Reading Fluency. Reading Fluency measures the speed at which the subject can read while maintaining good comprehension and it is the only test of the three which is timed.

Visagraph Results

The average number of fixations for all the subjects was 91.47 (norm for grade 18 is 44) with a standard deviation of 23.06. The average fixation duration for all the subjects was 0.25 seconds (norm for grade 18 is .22) with a standard deviation of 0.02 seconds. The average number of regressions for the all subjects was 8.59 (norm for grade 18 is 2) with a standard deviation of 5.88 (see Table 1 for summary). All of these values are greater (worse) than the grade norms for grade 18. This was not an expected result since the subjects were assumed to be generally proficient in reading due to their level of education. The highest paragraph difficulty is level 10 but norms are extrapolated up to grade 18 so that may be one reason for the discrepancy. Based on their Woodcock Johnson III reading scores results, there was no overall depression in reading ability. The Visagraph comprehension scores were not considered in this analysis so while the two reading measures are not directly comparable, the results may indicate that the Visagraph is not a good predictor of overall reading skill or that eye movement efficiency does not directly relate to reading skill for this subject group.

Pearson correlation coefficients were calculated for the three different Visagraph measurements (see Table 2). Number of fixations and number of regressions were highly correlated (.826, p<.001) which is expected because of their relation to eye movement efficiency (higher numbers on both indicate a greater frequency of eye movements during reading). There was no correlation between fixation duration and fixations or regressions. A longer duration of fixation means that the eyes need to pause longer at each fixation in order to decode the necessary information. While longer durations indicate less efficiency and longer cognitive dwell time, it was not necessarily expected that these values would correlate with the frequency of eye movements (fixations and regressions) although a positive correlation would have been logical since higher numbers on all these measures point to poorer reading skill.

Relationship between reading measures

Pearson correlation coefficients were also calculated for the Woodcock Johnson III readings tests and the Visagraph results to evaluate how these different measures of readings related to each other (see Table 2). There were significant correlations between the number of fixations with Reading Fluency, Passage Comprehension, and the Broad Reading cluster score. The negative correlations with Reading Fluency (-.511, p=.043) and with Passage Comprehension (-.549, p=.028) are logical because these are the tests which require eye movements (Letter Word Identification is one word identification). Higher reading scores would therefore correlate with more efficient eye movements (fewer fixations).

Descriptive Statistics – Reading Measures (Standard Scores)

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Letter Word Identification	16	47	78	125	104.44	10.78
Reading Fluency	16	63	74	137	106.44	16.21
Passage Comprehension	16	57	76	133	104.94	14.15
Broad Reading	16	57	77	134	108.63	16.60
Fixations	16	90.5	41.0	131.5	91.47	23.06
Fixation Duration	16	.08	.20	.28	0.25	0.02
Regressions	16	24	1	24	8.59	5.88

Table 1: Descriptive Statistics – Reading Measures

Reading Measure Pearson Correlations

		Letter Word Identification	Reading Fluency	Passage Compre-hension	Broad Reading	Fixations	Fixation Duration
Reading Fluency	Correlation	.397	1				
	Sig. (2-tailed)	.128					
Passage Comprehension	Correlation	.525*	.415	1			
	Sig. (2-tailed)	.037	.110				
Broad Reading	Correlation	.591*	.955**	.633**	1		
	Sig. (2-tailed)	.016	.000	.008			
Fixations	Correlation	-.036	-.511*	-.549*	-.555*	1	
	Sig. (2-tailed)	.894	.043	.028	.026		
Fixation Duration	Correlation	-.318	-.402	.093	-.362	.191	1
	Sig. (2-tailed)	.230	.123	.732	.169	.479	
Regressions	Correlation	-.089	-.424	-.473	-.472	.826**	.203
	Sig. (2-tailed)	.743	.102	.064	.065	.000	.451

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Table 2: Reading Measure Pearson Correlations

Coherent Motion Results

There are no established averages for the coherent motion threshold values under these different background color conditions therefore the conditions must be compared to each other rather than to a standardized mean. As shown in Table 3 and Figure 3, the mean threshold for the white background was 17.23 % with a standard deviation of 4.86. For the colored backgrounds, the mean thresholds varied from 15.25 % plus or minus 6.24 for the low contrast red background to 17.78 % plus or minus 5.49 for the high contrast blue background.

Descriptive Statistics – Coherent Motion Thresholds (%)

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Low Gray	16	20.42	8.31	28.74	14.70	5.17
High Gray	16	14.05	9.68	23.73	15.53	4.38
Low Red	16	22.19	9.08	31.27	15.25	6.24
High Red	16	18.13	8.42	26.56	15.30	4.49
Low Blue	16	19.18	10.99	30.16	17.47	5.66
High Blue	16	22.46	9.25	31.72	17.78	5.49
White	16	20.37	9.11	29.48	17.23	4.86

Table 3: Descriptive Statistics – Coherent Motion Thresholds

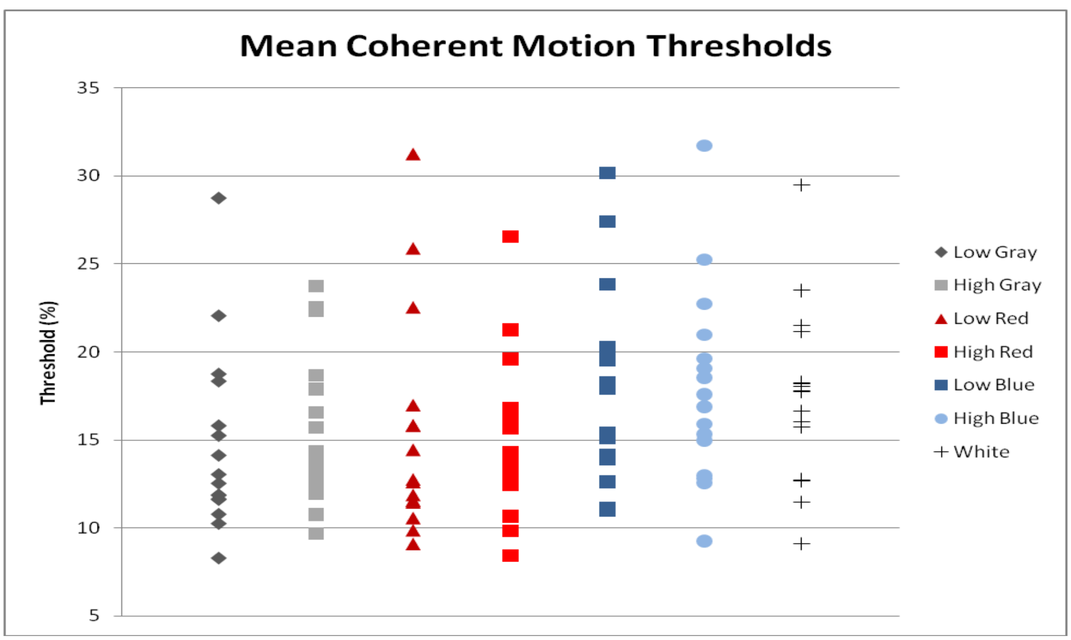

Figure 3: Mean Coherent Motion Thresholds

To determine whether the mean thresholds for the different color conditions were significantly different from each other, a two tailed analysis of variance (ANOVA) was calculated. While a repeated measures ANOVA showed a significant difference among the means (p=.0024), individual comparisons between color conditions showed that no pair was significantly different from each other. This indicates that there was not a specific change in motion sensitivity for the background colors used. The expected result was that the red backgrounds would result in the worst coherent motion sensitivities (highest thresholds), with the high contrast red having more of an effect than the low contrast red because of its higher intensity. It was also expected that blue backgrounds would increase coherent motion sensitivities (lowest thresholds), again with the high contrast blue having more of an effect because of its higher intensity.

The above data considered all the subjects together and only the individual threshold values at under each color condition were analyzed. It may be more useful to consider the change in threshold from the baseline value (white) in order to assess the effect of a colored background. This would help limit the washing out of significance if, for example, a subject overall has very high threshold scores, but certain colors change that score significantly. While the overall threshold scores for the different colors may be statistically equivalent, certain colors could have a significant effect on increasing or decreasing the motion sensitivity when compared to the white threshold.

Change in thresholds from a white background

This change analysis was completed for each color and the results were compared to the different measures of reading (see Table 4 for summary). There are no significant correlations between any reading measure and the threshold change from white and any of the red or blue color conditions, however the threshold change from the gray backgrounds do have significant correlations with several reading measures. The change in threshold between white and the low contrast gray color condition correlated with several of the reading measures, specifically Reading Fluency, Passage Comprehension, Broad Reading, number of fixations, and number of regressions. The high contrast gray background color condition showed a significant correlation only with Reading Fluency. The correlations with reading measures indicate that poorer readers gained more benefit from the reduced contrast gray background as they had higher increases in motion sensitivity (and presumably therefore improved magnocellular function) than better readers.

Threshold Change (%) from White and Reading Measure Correlations

		Low Gray	High Gray	Low Red	High Red	Low Blue	High Blue
Letter Word Identification	Correlation	-.473	.007	-.463	.124	-.026	-.231
	Sig. (2-tailed)	.064	.979	.071	.648	.922	.389
Reading Fluency	Correlation	-.635**	-.517*	-.205	-.297	.220	.134
	Sig. (2-tailed)	.008	.040	.447	.263	.412	.620
Passage Comprehension	Correlation	-.690**	-.072	-.467	-.155	-.238	-.423
	Sig. (2-tailed)	.003	.792	.068	.566	.374	.103
Broad Reading	Correlation	-.741**	-.445	-.338	-.252	.120	-.018
	Sig. (2-tailed)	.001	.084	.201	.346	.659	.947
Fixations	Correlation	.574*	.249	.360	.101	.159	.212
	Sig. (2-tailed)	.020	.353	.170	.709	.557	.430
Fixation Duration	Correlation	.403	.339	-.025	-.079	-.176	.095
	Sig. (2-tailed)	.122	.199	.927	.771	.515	.725
Regressions	Correlation	.621*	.144	.340	-.057	.155	.193
	Sig. (2-tailed)	.010	.594	.198	.833	.567	.473

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Table 4: Threshold Change from White and Reading Measure Correlations

Discussion

The results of this experiment are strictly applicable to only one small subject group of highly educated participants and therefore are not extendable to the general population. However, the results found that there were no significant overall effects of a colored background on magnocellular function as measured by coherent motion thresholds. There are likely several reasons why the results did not fit these expectations.

The first is the small sample size. With only 16 subjects, it is more difficult to show any significant results as individual subject variation competes heavily with between group variations. Secondly, the overall expectations do not take into account reading ability. With a small subject group of 16, any outliers have a profound effect. Red filters were expected to decrease the motion sensitivities if all the readers were normal by increasing magnocellular inhibition thus simulating a magnocellular deficit. Since there were a few readers below one standard deviation from the mean standard score of 100 on the Woodcock Johnson reading tests and since the group overall had below average Visagraph scores, the overall effect of the red background may have been diminished if several subjects already had decreased magnocellular function.

On the other hand, blue filters were expected to increase the coherent motion sensitivities of poor readers by removing magnocellular inhibition. Since most of the subjects did have average or above average Woodcock Johnson reading scores, it is possible that the overall effect of the blue background was diminished if most readers did not have decreased magnocellular function. In other words, in terms of reading ability, the subject group may have been too normal to show increased coherent motion sensitivities with a blue background but may have been too abnormal to show decreased coherent motion sensitivities with a red background. Future studies on this topic should divide subjects into two clear groups of proficient and disabled readers in order to more clearly discern an effect of wavelength on coherent motion thresholds and the magnocellular pathway.

When the change in threshold from a baseline white background is analyzed, a low contrast gray background significantly correlated with an increase in reading function as measured by the Woodcock – Johnson III Reading Cluster and the Visagraph II eye movement recordings. Given that coherent motion is a measure of motion sensitivity and thereby a measure of magnocellular function, the correlations between the change in threshold with a low contrast gray background and readings measures offer some interesting insight into previous conceptions of the mechanism for colored filter success.

The negative correlations between the change in threshold with the low contrast gray background and Reading Fluency, Passage Comprehension, and Broad Reading scores indicate that in participants with lower reading scores, the gray background resulted in a greater change in motion thresholds. To put this another way, subjects who were worse readers showed a greater improvement in motion sensitivity when they used a low contrast gray background. It is possible to conclude that the benefit derived from the use of the filters can be due to a decrease in contrast which causes an increase in magnocellular processing, a theory that has been demonstrated previously with other tasks (Spafford et al, 1995; Pammer and Lovegrove, 2001). This would explain why those with worse reading scores using the low contrast gray background showed the greatest improvement in motion sensitivities because poor readers are more likely to have magnocellular deficits than good readers. The high contrast gray background also had a significant positive correlation, but only with Reading Fluency. Here, the worse readers also showed a better benefit with a gray background, possibly showing that reducing contrast most affected those with poor scores on the test with the highest magnocellular involvement (none of the other reading measures were timed so slowed visual processing and/or inefficient eye movements would have less of an effect on test results). One important note is that the Letter Word Identification scores did not have a significant correlation with the threshold change caused by either gray background, presumably because this test does not require any eye movements and therefore may not relate well to tests of motion sensitivity.

There were also significant correlations between the change in threshold with a low contrast gray background and Visagraph II results which measure eye movement efficiency. The positive correlations between the benefit provided by the low contrast gray background and fixations and regressions also point to the idea that reducing contrast most helps those with poor eye movement efficiency. Subjects with higher numbers of fixations and regressions were the ones who showed greater decreases in coherent motion thresholds (greater increases in motion sensitivity) when using the low contrast gray background. The reduction in contrast here again seems to most benefit those with poor magnocellular function.

However, in considering the validity of these results, the Bonferroni correction which takes into account the number of comparisons made, results in a p value of 0.001. When considering the data at this significance level, the threshold change from a white to low contrast gray background was significantly correlated with the Woodcock Johnson

III Broad Reading score. This indicates that while the individual measures of reading (Reading Fluency, Passage Comprehension, number of fixations) may be correlated with the threshold change from a white to low contrast gray background, the Broad Reading score and overall reading ability remains as the only truly significant relationship.

The analysis between the threshold change when using a low contrast gray background and reading measures show that worse readings scores correlate with better improvement in motion sensitivity. This may indicate that true dyslexics with substandard reading scores would show an even greater benefit with reduced contrast than what was seen in this subject group since most had normal reading scores.

However if contrast reduction was the only factor in play, then there should also be some significant correlations between the low contrast red and the low contrast blue backgrounds (which have the same luminance as the low contrast gray background) with the measures of reading. The lack of these correlations suggests that, for this specific subject group, the addition of red or blue wavelengths disrupts the relationship between threshold change and reading function. This may be because most of the subjects had reading scores within the normal range; therefore any change in the timing of the magnocellular pathway by either color caused abnormal and unpredictable results. This same effect was seen in the study involving three tasks with increasing magnocellular involvement (Williams, 1992). When considering the last task which required subjects to free read a paragraph without any guidance, dyslexic readers did better with a blue filter but normal readers did worse with a blue filter and they did worse with a red filter. This shows that altering the timing by the introduction of a red or a blue filter caused a decrease in performance for normal readers.

In analyzing the results of this experiment, the simple reduction of contrast while keeping the balance between short and long wavelengths in the background for the coherent motion tasks proved to more relatable to subjects with lower reading scores and poorer eye movement efficiency even if they are classified as normal readers. It is possible that since the computer output of colors is not pure, there was partial blue in the red background conditions and partial red in the blue background conditions. This may have cancelled out any effect on motion thresholds and may explain why only the gray background showed a significant correlation with reading function. Since there were no correlations between the colored backgrounds and reading scores, no conclusions can be made about the effect of wavelength on coherent motion ability for poor or good readers.

Based on the results from this experiment and the many others dealing with dyslexia, visual processing, and colored filters, there is no clear conclusion that can be drawn regarding the cause of dyslexia, the role of the visual system, or the effect of treatments on the visual system and on reading performance. In the face of all the uncertainty and controversy surrounding dyslexia, treatment recommendations remain unclear.

First, we must consider that if dyslexia is a genetically based neurological problem (Paracchini et al, 2008), the deficits (phonological or visual) may be hard wired and no amount of therapy will be able to change that. However there is evidence that although dyslexic brains do have measurable differences from normal readers, this difference can change with treatment and therapy. A study which measured fMRI connectivity of normal readers and dyslexic readers showed a significant abnormalities in dyslexics when they were completing a phoneme mapping task (Richards and Berninger, 2008). After training in linguistic awareness, reading, spelling, and writing, the imaging differences between normal readers and dyslexic readers disappeared. Thus while dyslexia may be a neurological abnormality, it is not necessarily a permanent one.

Then there is the debate over whether dyslexia is due a phonological deficit, a visual deficit, or both. Likely, there is no one right answer, because it may be different for different people. But if a dyslexic reader does indeed have a visual processing deficit (in particular, one involving the magnocellular pathway), can therapy and training improve their processing skills? There are several studies which show that some amount of therapy can improve both motion processing and reading skill and efficiency. One study showed that computer game training significantly improved the temporal processing skills of children who had reading impairments, indicating that temporal processing deficits can be ameliorated (Merzenich et al, 1996). Another study followed disabled readers before and after several temporal vision processing therapy sessions (Solan et al, 2004). Magnocellular function as measured by coherent motion and reading comprehension, oral reading, and word attack skills were all improved after fifteen 45 minute therapy sessions (while normal readers showed no change in any of the measures after therapy). These studies indicate that many dyslexics do have a visual deficit and that training can help improve reading skill.

We must also analyze the use of colored filters and their effect on reading skill. While there are many studies showing subjective and objective reading performance improvement with colored filters, there are also studies showing that there is no benefit or that any difference is due to a placebo effect (Spafford et al, 1995). A recommendation of using the lenses as a part of a dyslexic treatment/management plan must include a cost/benefit analysis of the monetary and time costs put into promoting and using a therapy that has not been proven to be successful. It is also important to ensure that using a filter or lens is not a substitute for more traditional methods of coping with dyslexia, such as special classroom instruction.

Consider the stances provided by some major medical organizations. The American Academy of Optometry and the American Optometric Association released a joint policy statement acknowledging that some people with reading difficulties have a defective visual processing system leading to a disruption of the coordination of visual pathways used in reading (AOA/AAO, 1999). This statement says that vision therapy cannot directly treat or cure learning disabilities or dyslexia, although it does say that therapy can improve visual efficiency and processing and can work in conjunction with other approaches such as educational instruction. The statement stresses that each disabled reader should have an individualized and multidisciplinary treatment and management plan. The American Academy of Pediatrics states that most dyslexics have a phonemic deficit and that a double deficit situation may occur with visual problems in addition to the phonological ones but that the two are not dependent (AAP, 2009). They recognize some research on magnocellular deficits but state that there is not enough evidence to make any clear conclusions or to recommend any treatments. Neither the AOA/AAO statement nor the AAP statement mention colored filters as an acceptable treatment method.

Much more research needs to be done on the effect of wavelength on coherent motion thresholds and the magnocellular pathway and how this relates to reading before any treatment based on these ideas can be recommended. Previous research and this experiment's results show that it is possible that some types of reading dysfunctions are related to a magnocellular deficit which can be improved with a lowered contrast. However the effect of color on the magnocellular system and on reading performance is unclear. A study investigating the effect of colored backgrounds on the coherent motion using true dyslexic readers instead of the mostly normal readers used in this study may show more significant results. While debate over dyslexia, its causes, and treatment recommendations continues on, further research into this topic can help shed new light on this controversial topic.

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