Article • Visual Neural Timing Problems May Interfere with Reading, Attention, and Memory: Looking Beyond 20/20 Acuity

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ABSTRACT

Much evidence has now accumulated to suggest that a fundamental deficit in developmental dyslexia (in older adults) and in traumatic brain injury (TBI) is impaired operation of the visual timing functions mediated by the magnocellular system. This review summarizes these deficits and how they can be remediated rapidly by a short period of exercises aimed at improving sensitivity to moving gratings. Such movement-discrimination exercises activate both low and high levels in the visual magnocellular system, affecting both feedforward and feedback pathways. The exercises seem to boost reading by improving visual attention, memory, and executive-control networks. If the exercises precede conventional vision therapy, then all targeted cognitive skills seem to improve. The effect on reading of correcting visual timing deficits in the magnocellular pathways suggests that visual-movement discrimination plays a very important part in the acquisition of reading skills, not only in people with dyslexia, but also in typically developing children. Moreover, this research supports the hypothesis that faulty synchronization of parvocellular with magnocellular visual pathways in the dorsal stream is a fundamental cause of dyslexia and argues that the phonological reading deficiencies in dyslexia are often secondary to impaired development of the visual magnocellular timing system. Our studies call for a paradigm shift from phonologically based to visually based methods for remediating dyslexia. Such a shift is needed as well for older adults and following concussion. Importantly, this adaptive training shows cognitive transfer to tasks not trained, significantly improving a person's quality of life rapidly and effectively.

Keywords: attention/memory/reading/executive control networks, cortical plasticity, magnocellular deficits, perceptual learning, remediating cognitive skills, timing deficits

Web-Based EHR Platform

The developmental optometrist often finds a new patient with 20/20 acuity, yet who reads words very slowly and with many mistakes. This is a tell-tale sign of developmental dyslexia (DD), a problem that affects over 43 million people in the United States.[1] DD is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities that cause problems in reading comprehension.[2] What are the best tests to reveal the source of this problem? This review will present convergent evidence that these reading problems involve neural timing issues caused by impaired development of motion-sensitive cells (magnocellular neurons) in the visual system. This review will also demonstrate that in those with dyslexia, magnocellular deficits can be detected in the retina, lateral geniculate nucleus (LGN), and the visual cortical areas V1 and V3. The latter provide the input to the visual-motion areas, the middle temporal (MT) and medial superior temporal (MST) cortex, and to the dorsal visuomotor and attentional processing pathway. These deficits affect both feedforward and feedback pathways between visual, parietal, and frontal areas.

In treating dyslexia, there has recently been a shift from analyzing component-process deficits to measuring outcomes. This deemphasizes possible etiological mechanisms of dyslexia (phonology, visual processing, oculomotor, etc.) and thus leaves clinical researchers in the difficult position of not being able to appeal to causal theories to justify their approaches. One consequence of this change has been an emphasis on confirming a failure to respond to adequate instruction prior to diagnosis, the so-called "response to intervention" (RTI). Thus, since 2013, research has shifted away from possible causes of dyslexia and more towards ensuring the correct and equitable use of the diagnosis, exemplified by the RTI movement.[3] This paper seeks to present the growing scientific evidence that the symptoms of dyslexia (poor word accuracy, reading rate or fluency, and reading comprehension) are well explained by neural timing deficits and suggests a return to considering possible neurobiological causes of the disorder. This approach has many potential advantages for the clinician, including the development of novel treatments based on training to mitigate visual timing deficits.

Neuroscience of Motion Processing

The parvo (pattern) visual pathways are most active during stable fixation and have a response time about 10 msec slower than the magno (motion) pathways. However, in people with dyslexia, magno pathways have been found to be 20-40 msec slower than in those without dyslexia.[4-6] Therefore, in dyslexic patients, the motion and pattern pathways are not in sync or working together properly, so the brain's reading networks are slowed down. This slowdown causes problems with paying attention, multitasking, sequential processing, and remembering visual forms easily,[7-14] as shown in this short movie: https://youtube/LDdhuhPeXNI.

The visual system has a fast magnocellular channel for the purpose of selective attention, together with a slower parvocellular channel.[15,16] Normally, the magnocellular pathways signal fixation on the beginning and end of a word as well as the location of individual letters.[17] The word's overall form is deciphered by the parvocellular pathways. Sluggish motion cells make it difficult to locate the beginning and end of a word or to identify the order of letters in it, causing mis-sequencing and confusion; hence, slow reading, as shown in Figure 1. Thus, slow neural pathways cause the brain to misdirect visual attention, confuse what the eye sees, and reduce the ability to remember the visual forms of words.

The Role of Magnocellular Deficits in Dyslexia

The magnocellular and parvocellular pathways project from the retina, through the LGN (in different layers), to the visual cortex, where they bifurcate into dorsal and ventral visual pathways.[18] The magocellular timing pathway is thus specialized for processing the location and movement of objects in space.[19-23] It projects from the primary visual cortex, V1 (layers 4Cα and 4B), V2 (thick stripes), through visual area MT to the MST area.[18,24] Then it projects into the intraparietal sulcus of the posterior parietal cortex (PPC), a selective spatial-attention area[25] that is also involved in event timing.[26] The PPC provides

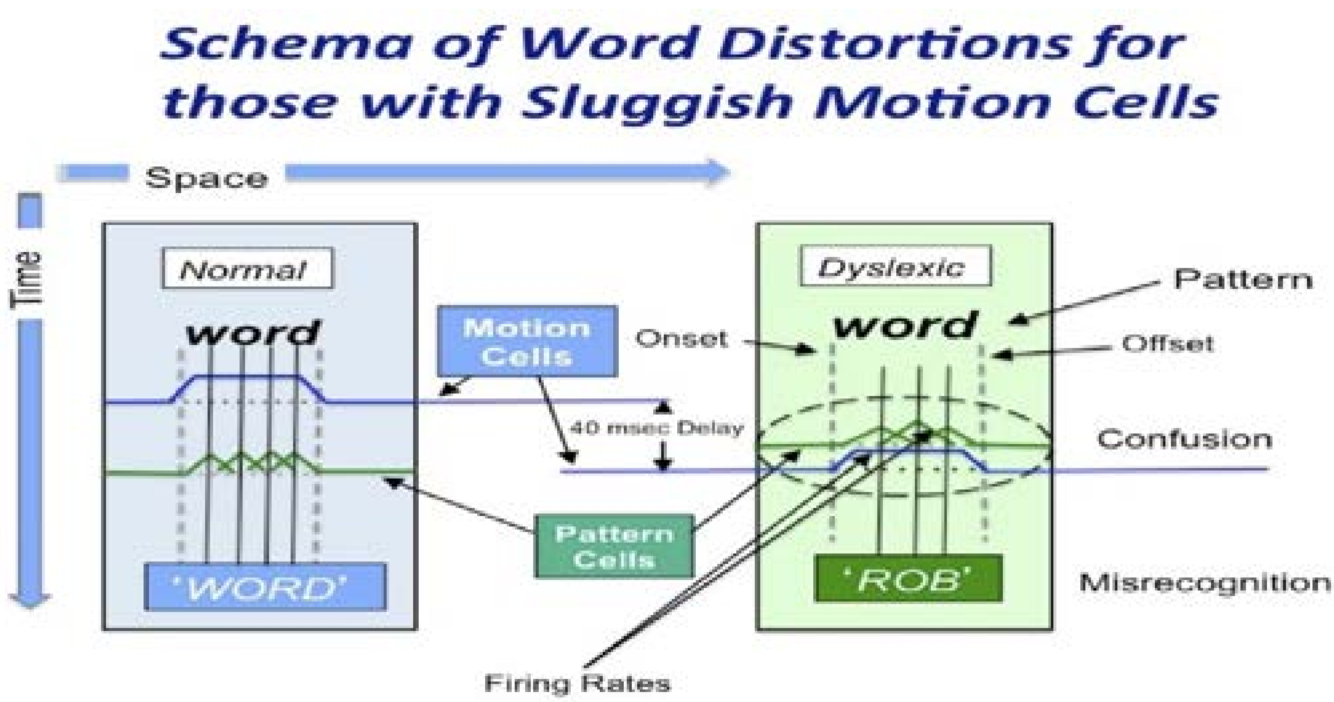

Figure 1. *Word distortions caused by magnocellular timing deficits preventing word location from being detected before deciphering individual letters.*

the input to the dorsolateral prefrontal cortex (dlPFC), where working memory is encoded. These are also the predominant cortical areas involved in executive control.[27] This is in contrast to the ventral stream, which receives both magnocellular and parvocellular inputs as it projects from V1 (layer 4Cβ) to V2 (thin stripes and interstripes), V3, V3A, V4, and V6[28] and on to the inferotemporal (IT) cortex, an area specialized for extracting the details related to an object's color and shape.[18,19,22,23] The faster transmission time of the magnocellular neurons projecting predominantly to the dorsal stream enable it to feed back to the striate cortex and to the ventral stream in order to direct parvocellular neurons to decipher the individual letters in a word.[8,9,15,16,29-31] Moreover, feedback in the dorsal stream from MT to V1 improves figure/ground discrimination,[32] which is required when reading to distinguish the letters in the word being fixated from the surrounding text. Furthermore, feedback from MT has its strongest effects for low-salience stimuli,[32] such as low-contrast patterns having less than 10% contrast; i.e., those patterns that maximally activate magnocellular neurons.[33,34]

People with dyslexia have magnocellular responses that are 20-40 msec slower than are found in typically developing observers;[4,5] this is 2-4 times slower than the normal magnocellular lead time of 10-20 msec.[6,35] Some investigators hypothesize that in those with dyslexia, a lack of synchronization in timing between magnocellular and parvocellular activations may prevent effective sequential processing, pattern analysis, and figure/ground discrimination and hence impede the development of efficient reading and attention skills.[7-11,14,15,29,30,36-43] Our working hypothesis[9,39] is that in those with dyslexia, the magnocellular neurons in the dorsal cortical visual pathway (V1-MT) are sluggish, causing visual timing deficits at all levels of visual processing.[4,5] These disrupt processing in the dorsal stream, as shown by those with dyslexia having reduced activity in MT.[44,45] These visual timing deficits thus limit patients' reading acquisition.

Convergent evidence confirms that many of those with dyslexia demonstrate impairments in movement-discrimination tasks that rely upon magnocellular functioning. People with dyslexia have been found to have motion-perception deficits at each of the following processing levels in the magnocellular (motion) stream:

1. The retinal level when measured using the frequency-doubling illusion[46-49]
2. The LGN, where the magnocellular layers have been found to be 30% smaller and more disorganized[5,50]
3. V1, measured using VEPs[4,5,51,52]
4. V1 and MT, using both fMRI brain imaging[44,45] and magnetoencephalography (MEG) brain imaging,[11,12] as well as psychophysical tests of movement discrimination relative to a stationary background[7-10,14,36-39]
5. MT, using motion coherence for direction discrimination[53-58]
6. Lateral intraparietal cortex (LIP) and frontal eye fields (FEF), anterior cortical areas activated by saccades, based on saccade and anti-saccade training tasks,[59] causing text to appear to move, a symptom that many people with dyslexia report[60,61]
7. Parietal structures, prefrontal language systems, cerebellum, basal ganglia,[62] and hubs of the attention networks.[11-13]

These results suggest a strong relationship between dorsal-stream processing and reading ability, such that poor dorsal-stream processing caused by sluggish magno (motion) cells is associated with both slower timing and poorer reading skills.[7-11,14,15,29,36,37,40-43,48,55,56,63,64] In fact, motion sensitivity in individuals predicts orthographic reading skills in both good and poor readers.[65,66] People with dyslexia have sluggish motion cells that do not signal the pattern-sensitive cells properly, causing difficulty in isolating and identifying the critical elements needed for reading, such as the beginning and end of the word and the order of its letters. Overall, research finds that there is an imbalance between magno- and parvocellular systems in those with dyslexia.[67] People with dyslexia therefore lack the ability to process sequential information quickly and accurately, causing deficits in both reading speed and comprehension.

Left-right movement-discrimination training[7-9,14,39] uses a key motion metric by measuring the contrast sensitivity for discriminating the left or right direction of a moving pattern.[68] Cells in the motion area MT are optimally tuned to the direction of moving patterns[69] and are activated optimally by low-contrast patterns.[34] In movement-discrimination training, the direction of movement is tested relative to stationary, textured background patterns that enable the lowest contrast thresholds for movement discrimination to be measured.[70-72] This paradigm uses a configuration found in natural scenes; e.g., when following the movements of a bird as it circles down to its nest in a lagoon, disappearing and reappearing against the camouflage of the landscape. Only when movement discrimination is done relative to a background do all types of dyslexic patients show movement-discrimination deficits.[7-9] Moreover, these moving patterns must consist of dim achromatic stripes, since these are the patterns optimal for activating motion (magno) cells. In fact, once the contrast (difference in luminance between dark and light bars) exceeds 10%, the magno cells saturate and no longer convey new information to higher processing levels.[33] Normally, the motion cells signal not only the beginning and end of each word, but also shifts of attention or eye movements from letter to letter, enabling the high-resolution pattern cells (parvocellular neurons) to attend to each and fill in the details. However, when the motion cells are not fast enough, this delay causes many problems.

Improving Magnocellular Function Improves Feedback from Higher to Lower Cortical Areas

The particular movement-discrimination training patterns[7-10,14,37-39] are vertical sinewave gratings; they were designed to activate motion-sensitive (magnocellular) neurons differentially in the V1-MT network[22,32,73-75] relative to pattern-sensitive (parvocellular) neurons. Therefore, they are effective in improving magno-parvo integration timing deficits at both low and high levels of visual motion processing. Improving contrast sensitivity for figure/ground discrimination (moving test stripes vs. stationary background stripes) is needed in order to provide an effective training stimulus to improve dorsal stream function.[7-10,14,39]

Direction discrimination using motion coherence has not been found to be such an effective training paradigm[78] because only in MT and higher processing levels are neurons selectively sensitive to motion coherence.[76,77] Instead, we use vertical sinewave gratings for contrast sensitivity-based movement-discrimination training,[7-10,14,37-39] since these differentially activate all motion-sensitive neurons, beginning peripherally in the retina and continuing to all subsequent visual cortical areas. Studies that have questioned the hypothesis that people with dyslexia have magnocellular deficits[79-82] have tended to use stimuli that are not optimal for activating direction-selective cells in the early V1-MT network,[74,83] using either flicker or high-contrast random dot patterns without a background pattern.

When reading, it has been proposed that the PPC uses the spatial information of the location and overall shape and form of a word that is received through the rapid motion-sensitive pathway to gate the information that is going through the ventral temporal stream.[15] The information is gated via attentional feedback to the striate and inferotemporal cortex and other regions in the occipitotemporal cortex,[15,84-86] most likely done by top-down feedback, which uses synchronized neuronal oscillations at the lower end of the gamma (30-100 Hz) frequency range.[16] This in turn is used by the pattern-sensitive neurons in the ventral stream, using coupled alpha/gamma oscillations regulated by the pulvinar for sequential processing,[87] as a starting point for deciphering the individual letters.[15,16] In fact, the visual word form area (VWFA) in the ventral stream, where the visual shapes of words are analyzed in detail,[88] receives significant magnocellular input from the dorsal stream to direct the VWFA's attention to which word it should analyze next.[16,89] It is likely that the dyslexic reader's deficit in attentional focus[15,29,90,91] is a consequence of sluggish motion-sensitive neurons preventing the linked pattern-sensitive neurons from being able to isolate and sequentially process the relevant information that is needed for reading,[15,29,92] and not from an information overload, as was proposed previously.[93]

Each cycle of gamma oscillation focuses an attentional spotlight on the primary visual-cortical representation of just one or two letters in order to recognize those letters in the right sequence to concatenate them into words.[16] The timing, period, envelope, amplitude, and phase of the synchronized oscillations that are modulating the incoming signals to the striate cortex have a profound influence on the accuracy and the speed of reading. The speed determined by the gamma frequency oscillation is the essential rate-limiting step in dyslexia.[16] It is proposed that impaired theta- and gamma-frequency oscillations in the visual domain hinder effective visual temporal sampling and parsing of text.[94] Cross-frequency theta/gamma coupling enables sensory areas of the brain, which capture language stimuli to communicate rapidly with higher-order brain areas for real-time processing of language input.[94,95] Sequential processing uses the functional anatomy of the claustral connections of items being processed serially, such that cross-frequency coupling between low-frequency (theta) signals from the claustrum and higher-frequency oscillations (gamma) in the cortical areas is an efficient means for the claustrum to modulate neural activity across multiple brain

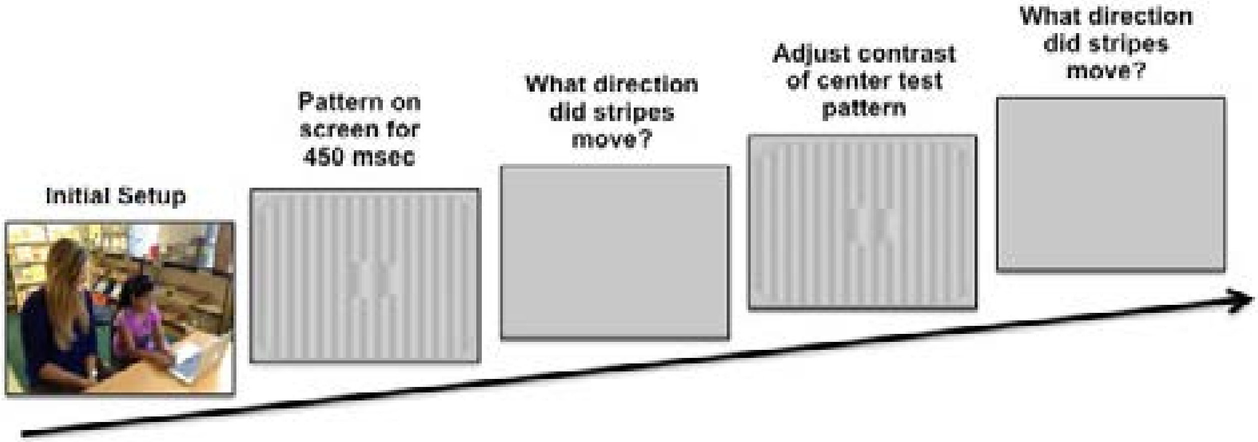

Figure 2. *Schematic of stimulus presentation for movement-discrimination training. The pattern flashes on the screen (shown above) while the center stripes move left or right. The screen goes blank, waits for left or right arrow key to be pushed. If incorrect, a short tone sounds. A pattern with the same or different contrast flashes on the screen, while the center stripes move left or right. The screen goes blank, waits for left or right arrow key to be pushed. This sequence of patterns is presented continuously until the contrast threshold for this pattern is measured. Then the next pattern combination is presented to measure the next contrast threshold until all 20 patterns are presented. The program says '"thank you," presents a star for each level of complexity completed, and quits.*

regions in synchrony.[96] In addition to the claustral connections mediating this theta/gamma cross-frequency coupling, coupled alpha/gamma oscillations regulated by the pulvinar are also used for sequential processing[87] to read words. Both claustral connections[96] and the pulvinar complex[87] regulate synchronous information transmission between cortical areas based on attentional demands. Cross-frequency coupling is being recognized as an efficient means of communication between two cortical areas that is likely to play a crucial role in mediating working memory and in enabling learning.[97,98] Contrast sensitivity-based movement-discrimination training employing figure/ground discrimination improved not only magnocellular function and attention, but also improved magno/parvo integration and figure/ground discrimination, and it coupled theta/gamma activity for the test patterns moving at 5, 5.7, 6.7, and 8 Hz.[7-10,14] After doing movement-discrimination training, coupled alpha/gamma activity for test patterns moving at 10 and 13.3 Hz were the patterns that improved contrast sensitivity the most.[7-10,14] They were not discriminated until more slowly moving patterns had been learned.

How Does Movement-Discrimination Training Work?

The patented contrast sensitivity-based movement-discrimination program called PATHtoReading/Insight[38,39] uses dim grayscale patterns to retrain the brain's pathways. These patterns are designed to activate motion pathways (by using left-right movement) relative to the pattern pathways by using a stationary background that trains motion discrimination.[71] Each pattern is presented for less than half a second (Figure 2).

Only the contrast of the center stripes (the test frequency) in the fish-shaped object that moves left or right relative to a stationary striped background is dimmed, until the direction can no longer be seen. At the start of a session, both the test and background gratings are set to 5% contrast to ensure that the contrast of the test pattern is in the middle of the magnocellular contrast range.[33] Each time that the direction that the fish stripes moved is identified correctly, the contrast of the test grating is lowered until the first incorrect response is obtained. Following the first incorrect response, a double-staircase procedure is used to estimate the direction-discrimination contrast threshold, which allows for measuring the contrast sensitivity, defined as the reciprocal of the contrast threshold times 100. This staircase procedure estimates the contrast needed for 79% correct responses, providing the most sensitive, repeatable measurements of contrast sensitivity.[99] This training is adaptive on a trial-by-trial basis in response to the subject's performance, such that lower contrasts are presented in response to good performance, and this improves sensitivity to motion at each of four durations and as the complexity of the background increases. Moreover, the training incorporates cycles of feedback and reward at multiple levels, ranging from positive and negative feedback on a trial-by-trial level, as well as cumulative block and session feedback. Such feedback greatly accelerates learning.[100,101] A full training cycle of this movement-discrimination task requires 20 threshold determinations (i.e., one for each of the four test spatial frequencies (0.25, 0.5, 1, and 2 cyc/deg) paired with each of the five background spatial frequencies). The stationary backgrounds, consisting of single and multiple spatial frequencies at increasing levels of complexity, are chosen to bracket the test frequency, vertical gratings whose fundamental frequency equals the test frequency or ±1 or 2 octaves from it; these activate adjacent spatial frequency channels in V1 and MT.[74,102] There are therefore 24 levels of complexity, each increasing in difficulty slowly, from slow theta movement (5, 5.7, 6.7, 8 Hz) to faster alpha movement (10, 13.3 Hz) for both one (Motion program) and two (MotionMemory program) directions of left-right movement; Motion and MotionMemory being subprograms of PATHtoReading/Insight. Thus, a total of 48 levels of complexity are used to train the user quickly and effectively, improving the functionality of their dorsal attentional and executive function networks. The feedback to the user makes this a fun game that motivates them to continue to improve.

This contrast sensitivity-based movement-discrimination program[38,39] uses positive feedback that is provided in the form of catching more fish in the net, resulting from meeting specific thresholds (e.g., less than 1% contrast and through a score that increases as performance improves, as shown in Figure 3). There is also immediate feedback in the form of a beep if the user identifies the direction of movement incorrectly, in addition to other verbal feedback when needed. Simply interacting with a game-like training program on a computer for 30 minutes for 12-16 weeks, followed by problem solving, remembering, or reading, is all that is involved. A computer-based ReadingRate program, where the user reads 6 words at a time from an interesting story, provides an ongoing measure of reading speed during the training. When the words are read aloud with the student, then reading speeds increased 11-fold instead of increasing only 3-4 fold.[8]

Simply practicing left-right movement discrimination using patterns that activate the motion pathways improves the ability to think more quickly. In fact, brain imaging at University of California San Diego in Dr. Ming-Xiong Huang's lab has shown that after using movement-discrimination training for 15-20 minutes twice per week for 8-12 weeks, the function of the attention, problem-solving, and working-memory (executive-control) networks improves significantly.[11-13]

It is likely that completing the contrast sensitivity-based movement-discrimination exercises helps the brain to select the most efficient pathways to be used, enabling cortical function to be more focused. This results in improved multitasking, problem solving, and ease of learning. Movement-discrimination training is more effective when completed on a regular basis each week. Completing these movement-discrimination exercises every day creates effortless competence when stringing together every action and makes the process easier each subsequent time. This regular practice trains the brain to use and to ingrain those efficient pathways; it enables the string of different activities that are completed throughout a day to become increasingly efficient, as documented by many testimonials. The totality of actions necessary for learning and reading can seem overwhelming at first, but since movement-discrimination training improves all of them and helps to keep them all in the right order (sequential processing), it helps people to multitask and to organize their day more efficiently, as documented in many testimonials on pathtoreading.com. These movement-discrimination exercises enable learning new pathways that can be combined with positive thinking to change one's goals so that they are more in alignment with the direction one wishes to pursue in life. They provide a brain warm-up that enables anything practiced immediately afterwards to be noticeably easier than before, since the exercises improve attentional networks and executive function, enabling higher-order tasks to be completed more easily (and with less effort). Therefore, in order to obtain the greatest benefit from these movement-discrimination exercises and to prime the brain to learn more easily, they should be undertaken before other visually based brain exercises such as those that comprise vision therapies. Both contrast

Figure 3. *Feedback to provide information about how the patient is progressing on movement-discrimination exercises*

sensitivity-based movement-discrimination training and vision therapies are essential to improve the visual, attention, and executive-control pathways. Thus, only what is practiced following movement-discrimination training improves noticeably.

Improving Visual Magnocellular Pathways Remediates Reading Fluency, Attention Span, and Memory Retention

The sluggish magnocellular neurons in those with dyslexia not only result in attention deficits, an impairment in the low gamma frequencies that reduce feedback to visual cortical areas,[16] but they also disrupt processing in the lateral intraparietal (LIP) area.[15,59,68,103] This area keeps a salience map for the control of saccadic eye movements and visual attention[104] either within a fixation, between fixations in a sequence, or both. Its disruption causes very slow reading speeds. Moreover, finding that movement-discrimination training improved not only reading fluency, but also selective and sustained attention and working memory when carried out before reading,[9,12-14] indicates that movement-discrimination training helps develop the attention and executive control networks, since fewer resources are used to decode incoming information. Hence, more resources can be deployed to analyze the information, which improves visual, attention, reading, and memory skills. These results provide more evidence that impaired visual-motion processing is a fundamental cause of reading and attention problems in dyslexia and other cognitive slow-downs, like those caused by a concussion, evidence augmented by MEG brain imaging studies.[14] By improving the functioning of these attentional networks, movement-discrimination training provides a wider window of attention so that more objects can be perceived in their correct location in a single glance.[105]

Movement direction-discrimination training also improves the ability to detect the synchronicity of multiple objects in space and to see their trajectories over time. This most likely occurs by increasing the ease of magno/parvo integration, thereby facilitating figure/ground discrimination within a wider window of focused attention.[14] Importantly, improvements in reading speed after movement-discrimination training are sustained over time,[8] whereas improvements in word reading found to improve phonological processing following auditory interventions degrade over time. Two years later, patients showed no differences in word-reading skills compared to controls who did not complete the auditory intervention.[106]

Improving cognitive function by training contrast sensitivity-based movement-discrimination relative to a background is a novel technique[38,39] that is both rapid and effective in improving cognitive skills in people with dyslexia. Only when low-level visual timing deficits are remediated in those with dyslexia are the improvements in higher-level cognitive functions, such as reading fluency (speed and comprehension), attention, and working memory, improved quickly, with improvements that are sustained over time.[8] Contrast sensitivity-based movement-discrimination training[7-10,14,37-39] is the first visually based intervention that has been shown to improve both low-level movement discrimination in the dorsal stream and high-level cognitive functioning. This has been demonstrated both behaviorally and using MEG brain imaging, finding improvements in the attention and the executive control networks in people with dyslexia[11,12] and also following TBI.[13] Movement-discrimination training represents a paradigm shift in the treatment of dyslexia as it is based on improving visual timing instead of targeting higher-level phonological skills. Students who have to allocate all of their resources to identify the letters in the word—instead of being able to interpret the sentence, understand its meaning, and integrate the information into their existing knowledge—need movement-discrimination training first in order to remediate their visual timing deficits.

Visual timing deficits have been detected and remediated in all types of dyslexia (dyseidetic, dysphonetic, and mixed) when contrast sensitivity-based movement-discrimination training[7-10,14,37-39] was carried out for only 15-20 minutes 2-3 times per week for 12 weeks. This training also significantly improved reading fluency, processing speed, attention, and working memory, which are all high-level cognitive functions.[7-9,14,36,37] Improved reading speed can predict improved comprehension, grade level, spelling ability, and a host of other reading skills, since decoding has ceased to be a limiting factor. Moreover, this movement-discrimination training improved working memory and attention by improving dorsal-stream function at both low and high levels of processing.[9,14] In a previously published study of 21 participants undergoing movement-discrimination training,[14] large effect sizes were found for reading speed, reading comprehension, pronunciation, attention, visual working memory, and auditory working memory. These effects were substantially larger than found in a large meta-analysis examining other methods of improving reading skills in those with dyslexia.[107] In addition, after a short period of movement-discrimination training had been completed by dyslexic fourth graders, three times per week for 6 weeks, their dorsal stream activity improved significantly when assessed by visual evoked potentials.[52]

Contrast sensitivity-based movement-discrimination training improves the function of many related brain pathways, improving visual, attentional, and memory networks. In a recent pilot study, MEG brain imaging found significantly improved functioning in both the dorsal stream (V1, V3, MT, MST areas) and frontoparietal attention networks (ACC, precuneus/PCC, dlPFC) following 8 weeks of movement-discrimination training for 10-15 minutes twice per week in a 29-year-old with dyslexia.[11,12] The improvements in MT were found to occur in the first 300 msec, showing that the training sped up the magno cells in the dorsal visual pathways. These benefits were shown both by the brain imaging studies and behaviorally: reading speed increased from 154 to 437 words/min (reading 6 words at a time from an interesting story using a computer-based program), selective and sustained attention improved an average of 22-fold (measured using IVA+Plus from BrainTrain), visual working memory increased from 6% to 99%, and delayed recall improved from 1% to 25% (both measured using the Test of Information Processing Skills) in only 8 weeks when doing movement-discrimination training for 15-20 minutes twice a week. The patient also improved in visual skills, markedly reducing his convergence insufficiency; his near point of convergence was improved from 9 cm to 3.5 cm.

The visual movement-discrimination training program PATHtoReading/Insight (https://pathtoreading.com) leads to improvements in cognitive skills for people with dyslexia. These improvements in cognitive skills were not found by improving auditory timing using FastForWord or through linguistic-based training using Learning Upgrade.[9] This was shown in 58 poor readers, 26 doing Learning Upgrade (control), 16 doing visual movement-discrimination exercises, and 16 doing auditory-timing exercises. Likewise, computer-based repeated reading using Raz-Kids failed to improve 21 students, whereas 21 doing visual movement-discrimination exercises improved greatly.[14] When compared to movement-discrimination training, repeated-reading interventions do less to improve reading fluency, as supported by our findings: 1) reading speeds improved only 2-fold following repeated-reading exercises;[104] instead following movement-discrimination neurotraining, a student read aloud from 3- to 11- times faster,[8] and 2) improvements in comprehension using repeated-reading interventions were much lower than achieved using movement-discrimination training. For example, Vadasy and Sanders[104] found that repeated reading aloud improved comprehension 8% as assessed by the Gray Oral Reading Test (GORT), whereas contrast sensitivity-based movement-discrimination training improved comprehension when assessed by the GORT by 28% for dyslexic students and 37% for typically developing students,[14] even though each group trained for half as much time as that employed by Vadasy and Sanders.[109] The improvements in reading fluency and other cognitive skills following movement-discrimination training were also found in typically developing children[14,37,39] who were in second and third grade (6 to 8 years old), which is the age when the temporal lobe shows peak synaptogenesis.[109] Since timing impairments can be reduced following movement-discrimination brain exercises,[9,14] these findings support the hypothesis that visual magnocellular pathways provide the gateway for attentive processing[15,16] and reading.[41,56]

The contrast sensitivity-based movement-discrimination intervention used by PATHtoReading/Insight is believed to improve the precision of timing of visual events and thus accelerate reading progress.[8,9,38,39] It achieves this by improving the function of the dorsal stream, boosting magnocellular relative to parvocellular activity, thereby improving inhibitory and excitatory circuits based on the data from neural plasticity. This theory is based on the idea that synchronous firing of neurons is what controls communication between different areas in the brain.[110] If neurons in one area are “sluggish” with respect to neurons in another area, then they will be unable to synchronize properly. Hence, processing speed will be slowed down and communication and learning will be compromised. The brain’s neuroplasticity extends throughout a person’s lifespan. Through extensive movement-discrimination training, we have found that we can continue to improve visual attention, executive control, and reading networks. Executive control is a strong predictor of life outcomes, such as academic achievement, since executive function is strongly associated with math ability and reading, writing, and language comprehension.[111] Movement-discrimination training[7-9,14,36-39] was one of only ten interventions that were found to improve executive function and brain fitness for students by Brain Futures.[112] Brain fitness neuroplasticity reveals that the neurocircuitry in the brain is highly malleable, continuing to grow and change for the duration of our lives.

Visually based movement-discrimination exercises in both normal subjects[7,14,37-39,70-72] and those with dyslexia[7-9,14,36-39] have demonstrated neuroplasticity in the domain of processing speed using massed practice. These studies found that the more movement discrimination was practiced, the more contrast sensitivity for movement discrimination, reading, attention, and memory skills improved, with gains in speed, accuracy, comprehension, attention, and working memory being measured using age-appropriate standardized tests for these cognitive skills. Not only was movement-discrimination training more effective, but also it required less than half of the training time used by other reading interventions.[9,14]

Neuroscience Underlying Improvements in Cognitive Skills After Movement-Discrimination Training

Our theory of change shows how improving contrast sensitivity-based movement discrimination (in V1-MT) improves high-level cognitive functions (in PPC, dlPFC). Visual movement-discrimination training targets the temporal dynamics of the visual-attention and reading pathways. We propose that by improving the slow processing speed of magnocells at low levels of the visual dorsal stream (V1-MT), we are improving subsequently higher levels in the dorsal stream: both the PPC, improving visual and auditory attention, and the dlPFC, improving working memory, cognitive flexibility, problem solving, and subsequently reading speed and comprehension (Figure 4). This movement-discrimination training is hypothesized to enhance coupled theta/gamma and alpha/gamma oscillations,[9,11,14] improving both the feedforward and feedback attention and executive control networks conveyed by the dlPFC and PPC[25] to modulate attention in MT and V1, enabling a wide range of cognitive skills to improve. By using repeated exposure to stimuli optimal for improving the brain's visual timing (via motion discrimination), contrast sensitivity-based movement-discrimination training increased comprehension, attention, and memory from one to four grade levels and reading speeds between 2- and 11-fold.[7–9,14,38] Neural connections are strengthened to repair dysfunctional connections, enabling the most efficient pathways to be used, thereby improving a person's ability to learn. Movement-discrimination training takes advantage of the brain's plasticity to improve the function of pathways so that they work together and significantly improve reading, attention, and memory when followed by a vision therapy regimen that enables practicing these cognitive skills.

Vision therapy is designed to improve fixation and saccadic versional eye movements, as well

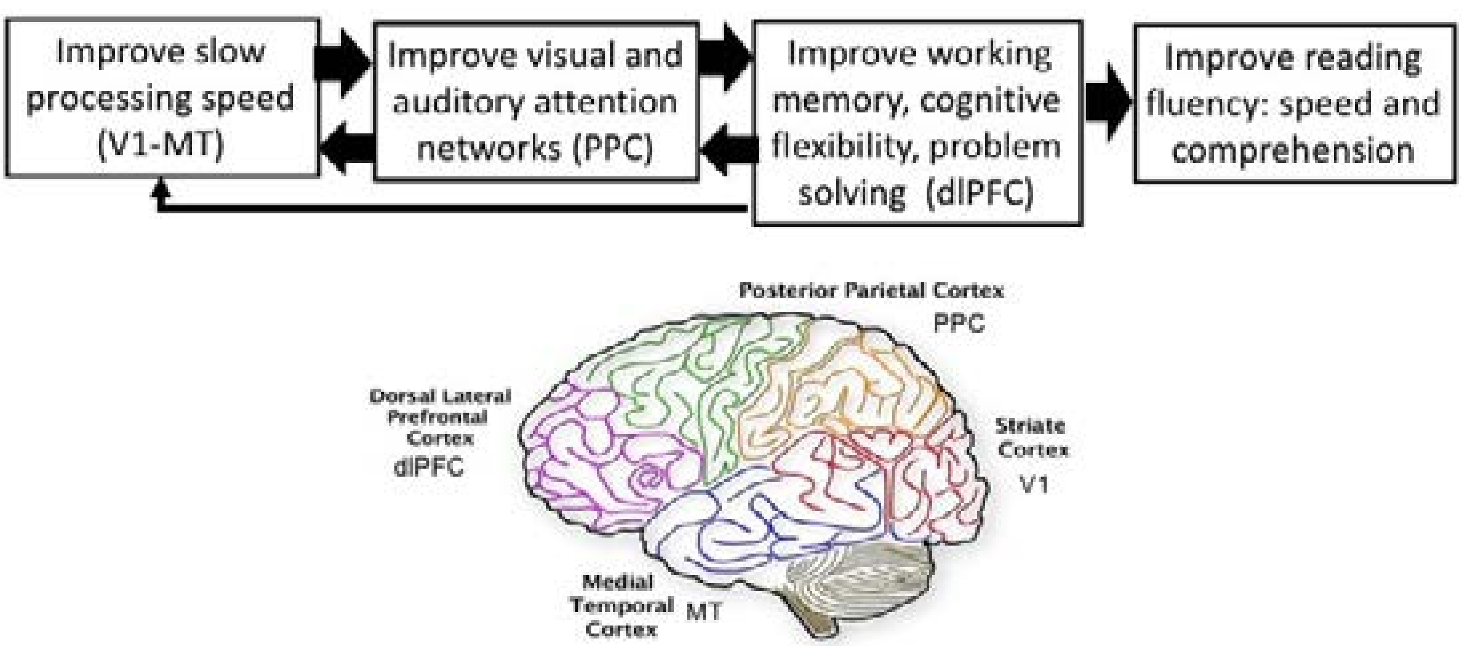

Figure 4. *Theory of change proposes that low-level timing deficits (V1-MT) impede processing at subsequently higher cortical levels of processing, using both feedforward and feedback pathways. These low-level timing deficits are a limiting factor causing impairments in cortical processing for dyslexia, aging, and concussion.*

as to promote coordination between vergence and accommodation.[113] Coordination of the three oculomotor systems (version, vergence, and accommodation) is important for efficient reading. In addition, the value of adding motion-sensitivity tests to the vision therapy regimen, which is not ordinarily performed in the optometric evaluation of those with dyslexia, has been shown.[109] Vision therapy regimens that improve saccadic tracking have been found to improve reading fluency in young children.[110] Since saccadic tracking is controlled by LIP and FEF, anterior cortical areas in the dorsal stream,[59] optometrists Drs. Ingryd Lorenzano and Jill Ingelse (personal communication), find that improving low-level cortical areas in the dorsal stream using contrast sensitivity-based movement-discrimination training accelerates progress and is more effective in improving reading fluency, greatly reducing the need for eye-tracking training. Therefore, completing movement-discrimination training at the beginning of a vision therapy regimen has the potential to improve the speed and effectiveness of the therapy program.

Following contrast sensitivity-based movement-discrimination training, not only have improvements in visual and cognitive skills been found for people with dyslexia, but they have also been shown for older adults.[11,105] A 71-year-old patient had movement-discrimination training for 15-20 minutes twice per week for 8 weeks. Standardized neuropsychological tests were administered before and after the training and showed significant improvements in visual skills. The Adult Dyslexia Test score improved from markedly or mildly below normal for dyseidesia and dysphonesia, respectively, to above normal for both. In addition, both working memory and attention improved. Visual working memory (measured using the Test of Information Processing Skills) improved from 34% to 86%, and auditory working memory (measured using the Wechsler Adult Intelligence Scale (WAIS)-IV) improved from 55% to 97%. The patient was already adept at paying attention (measured using the Delis Kaplan Executive Function System (DKEFS) Color-Word Interference Test) yet still improved after training from 81% to 87%. She also improved substantially in processing speed (measured using WAIS-IV), from 42% to 77%, more than doubling her reading speed (229 wpm to 541 wpm when reading 6 words at a time from an interesting story using a computer-based program), as well as problem solving, improving from 73% to 95% on the Wide Range Achievement Test (WRAT) math subtest.[11] Although she was only one subject, her large improvements confirm many previous reports of improvements in cognitive skills involving the executive-control network.[101] Since coupled alpha/gamma activity is reduced in older adults with mild cognitive impairments,[111] these improvements in working memory provide more evidence that movement-discrimination training can improve coupled alpha/gamma activity.

As indicated by recent scientific studies, magnocellular deficits are a major factor in problems experienced by those with dyslexia, attention deficits, aging, and concussion.[7-16,36-45,116] Clearly, there is a need to provide movement-discrimination training not only for people with learning problems caused by dyslexia, speech and language problems, or attention deficits, but also for individuals who are older adults or those who have sustained a concussion or traumatic brain injury.

Not Only are Timing Deficits Found in Dyslexia and Older Adults, They are also Found After a Concussion

After a concussion, the neural networks for attention and working memory are disrupted.[13,117-119] These patients typically have trouble sustaining attention.[120] Cognitive deficits in those with a TBI are hypothesized to result from neural timing deficits.[121] Compensation for timing issues by increased prefrontal cortical recruitment would manifest as increased distractibility, working-memory deficits, and problems with balance and coordination. This may lead to fatigue, headache, irritability, anxiety, and when prolonged, depression.[121] Visual timing deficits resulting from magnocellular (motion) deficits often persist after a TBI[122] because they cause timing deficits in the dorsal pathways and in the attention and executive-control networks.[13,121] In one case series, Lawton and Huang[13] found that improving visual timing in four male TBI patients significantly improved working memory and attention. These neural timing improvements were achieved using contrast-sensitivity based movement-discrimination training. Such improvements were found in all of the TBI patients who completed this contrast sensitivity-based movement-discrimination program. Substantial MEG signal increases in the motion networks (V1, V3, MT, MST) and the attention/memory networks (ACC, precuneous/PCC, and dlPFC areas), as well as significant behavioral improvements in movement discrimination, processing speed, reading speed, attention using several different tests, and both auditory and visual working memory, were found for TBI patients following contrast sensitivity-based movement-discrimination training two times per week for 8-16 weeks.[13]

It is likely that the movement-discrimination training paradigm improves not only magnocellular function, attention, and memory, but also attentional feedback to V1 and MT that can be measured by the strength of coupled theta/gamma and alpha/gamma frequency oscillations.[16] Improvements in delta, theta, alpha, gamma, and beta interactions were demonstrated by Huang et al.[123–127] and will be studied some more in collaboration with Huang and his team shortly, in addition to MEG pre/post imaging after contrast sensitivity-based movement-discrimination training. Furthermore, there is evidence that the improvements in cognitive skills after this movement-discrimination training are sustained over time.[8,9,14] Thus, contrast sensitivity-based movement-discrimination exercises seem to improve not only attention, but also processing speed, reading speed, problem solving, and working memory, probably because less effort has to be spent decoding information, hence more effort is available for interpreting the information, improving timing and using the working-memory network more efficiently.[27] The success of contrast sensitivity-based movement-discrimination exercises in TBI patients[125] marks the first time that improving low-level visual timing deficits in the dorsal stream has been shown to improve high-level cognitive functioning, both behaviorally and using a biomarker, MEG physiological brain recordings.

Other cognitive training programs seem 1) to have little effect on improving the executive functions and attention in TBI,[126,127] 2) to be neither robust nor consistent, with transfer and sustained effects that are significantly limited,[128] and 3) to improve only the task being trained and not to generalize to tasks not trained or to everyday cognitive performance.[100] Currently, there are no proven solutions to improve attention and working memory in TBI patients.[125,129-131] However, not only attention and memory, but also reading and processing speed, improved significantly in TBI patients after a short period of movement-discrimination exercises.[13] Recovering these cognitive skills can improve a person's quality of life greatly after a TBI.

Novel Remediation to Improve Cognitive Deficits Caused by Timing Deficits

These findings show that by simply doing rapid brain exercises that improve a person's ability to discriminate left-right movement relative to a stationary background, the ability to read rapidly and accurately can be improved significantly. These patterns were designed to activate adjacent spatial frequency channels in V1, V3, and MT systematically.[74,102] In addition, reading comprehension, processing speed (timing), attention (both sustained and selective), and working memory (both visual and auditory) improved significantly after a short period of training.[8-10,14] These movement-discrimination eye-brain exercises can be used not only to detect slow reading, dyslexia, and other developmental problems (such as speech and language, attention deficits, and concussions) earlier than other methods, but they can also be used to remediate the cognitive deficits rapidly and effectively, as shown in controlled validation studies in schools and with individual patients,[7-9,14,37] by improving the brain's timing.[11-13,52]

Conclusions

What emerges from these multiple studies is the essential role of the magnocellular pathways in reading fluency, selective and sustained attention, and working memory. Short movement-discrimination exercises can improve visual movement sensitivity and figure/ground discrimination. This is followed by improvements in all types of dyslexia, so that reading and learning can be done more automatically. Training visual dorsal stream function at low levels (via the V1-MT pathways) significantly improved these high-level cognitive functions, probably by increasing the neuronal sensitivity and temporal precision of magnocellular neurons in the dorsal stream relative to linked parvocellular neurons in the ventral stream. Movement-discrimination training was faster and more effective in improving reading, attention, and memory than found after training using 1) repeated-reading interventions, 2) interventions designed to improve auditory timing, or 3) linguistic-based reading interventions. The success of contrast sensitivity-based movement-discrimination exercises for remediating visual timing deficits in the dorsal stream has confirmed the causal role of visual motion sensitivity in reading acquisition in those with dyslexia and typically developing children. Moreover, this research supports the hypothesis that faulty timing in synchronizing the activity of parvocellular with magnocellular visual pathways in the dorsal stream is a fundamental cause of dyslexic reading problems and argues that the phonological reading deficiencies in dyslexia are often secondary to impaired development of the visual magnocellular timing system. These studies suggest that a paradigm shift from phonologically based to visually based methods is required for the treatment of dyslexia. In older adults and following concussion, the same paradigm shift is also called for. Moreover, this adaptive training, with substantial feedback and rewards, shows cognitive transfer to tasks not trained and can thus help to improve a person's quality of life rapidly and effectively.

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