TRANSIENT & SUSTAINED PROCESSING

A DUAL SUBSYSTEM THEORY OF READING DISABILITY

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Abstract

In this article the author reviews the concept of interactive processing that involves two parallel, segregated visual pathways, the transient and sustained processing systems. Evidence that deficits in the transient, but not the sustained system, interfere with the reading process is examined. After tracing these pathways from the retina to the visual cortex, and beyond, special attention is given to the mechanism of the dual processing system in reading, the synchronization of these two systems, and the effects of poor timing on visual processing and reading. Two successful treatment procedures for reading-disabled are described. The importance of integrating these concepts into optometric therapeutic procedures is discussed.

Key Words

transient, sustained, parallel processing, specific reading difficulty (SRD), visual perception, visual search, magnocellular, parvocellular

Recent research has shown that approximately 70% of children with SRD (specific reading difficulty) have specific visual deficits, i.e., a transient processing deficit. Approximately 80% of this group respond to a simple intervention which has immediate and dramatic effects on reading performance.[1]

The question of whether children who have trouble learning to read have a visual disorder that is causing the problem is a primary concern of behavioral optometrists. Heretofore, some optometrists and educators have been hesitant to relate visual deficiencies to reading disorders. However, considerable research that reports significant correlations between visual and perceptual skills and reading in normally achieving elementary school children is available.[2,3] Nevertheless, there is a scarcity of controlled intervention studies that could potentially establish cause and effect.

Although visual handicaps often are excluded as primary determinants of reading disabilities, in some instances visual and perceptual-motor problems are contributory, making it profoundly difficult for the individual to respond to educational intervention. There are a number of explanations why the experimental evidence supporting the view that the correction of visual dysfunctions contributes to improvement in reading has been equivocal. Suchoff[4] observed that the general inability of research to relate vision clearly to reading has not been faulty design or statistical treatment (though these have occurred) but rather has been due to the way most researchers have chosen to characterize the visual process. Experimental design, specific characteristics of the sample of the population used, and choice of visual tasks and measures of reading ability are additional possible sources of concern. For the purpose of this discussion, a specific reading disability (SRD) is defined as: "An unexpected inability to learn to read despite conventional instruction, adequate intelligence, average progress in other subjects, and normal socio-economic opportunity."[5] At least some of the experimental problems can be attributed to the ambiguous, if not controversial, definition of reading disability and, to a lesser extent, the lack of preciseness in defining some of the visual dysfunctions.

Reading involves a visual processing task that requires the analysis of features of visual patterns.[6] Optometric research with children has demonstrated that a significant correlation exists between the rate of visual processing and reading skills.[7] Poorer readers process information more slowly and have a more limited processing capacity than normal readers. This research methodology has depended upon experimental procedures that primarily involve visual-spatial processing. It would be incorrect, however, when comparing normal and disabled readers to conclude that the cause of reading disabilities is unitary and that all reading problems arise from a single inherent deficiency.[8] Indeed, during the past 10 years, there has been an accumulation of studies involving dual visual processing that has provided further evidence for basic visual processing differences between normal and disabled readers, especially at the early stages of visual processing.[9,10]

In this article, we will develop the concept of interactive processing that involves two parallel, albeit segregated, visual pathways, the transient and sustained processing systems. The former is characterized as motion-sensitive while the latter channel is described as pattern- or form-sensitive. Of special interest is the processing speed of each channel. We will examine the evidence that appears to support the notion that deficits in the transient, but not the sustained, system may be interfering with the reading process in 75% of disabled readers.[10] If it is the case that reading disabilities are attributable to visual deficits, then optometric researchers should concern themselves with the task of carrying out further studies to learn more about the nature of these visual processing skills that appear to differentiate normal and reading-disabled children. The ultimate goal is to augment the optometrist's diagnostic and therapeutic insight and skill in the management of this complex problem.

Retinal Ganglion Cells

The two systems originate in the retinal ganglion cells and extend, via the lateral geniculate nucleus (LGN), to the striate and extrastriate areas of the visual cortex. (For a complete and scholarly review, the reader is referred to: Garzia RP, Sesma M. Vision and reading I: neuroanatomy and electrophysiology. J Optom Vis Devel, Spring 1993; 24 [1]: 4-51.) Their influence then projects to the parietal, temporal, and sub-cortical areas of the brain. Two different types of ganglion and geniculate cells have been defined, M cells (magnocellular) and P cells (parvocellular). M cells comprise 10% of the retinal ganglion cells and are distributed evenly across the retina. They have larger receptive fields and are more sensitive to high temporal and low spatial frequency (below 1c/deg) stimuli. P cells comprise 80% of the retinal ganglion cells and are more concentrated in the fovea. They have smaller receptive fields and are more responsive to low temporal and high spatial frequency (greater than 10 c/deg) stimuli. In general, the response characteristics of M and P cells are similar to the attributes of transient and sustained channels, respectively.

Dorsal Lateral Geniculate Nucleus (dLGN)

The retino-geniculate pathways that consist of the axons of about 90% of the retinal ganglion cells terminate in the left and right dorsal lateral geniculate nuclei. (The ventral or pregeniculate nucleus of the LGN is undifferentiated in humans and is not relevant to this discussion.) The magnocellular neurons (M cells) project to the two ventral layers of the dLGN while the four dorsal layers are parvocellular (P cells). The two channels are differentiated in the retina and remain segregated in the primary visual cortex, but anatomically and histologically their separation is most apparent in the six layers of the dLGN. Although the principal function of the dLGN is to relay ganglion cell information to the visual cortex, less than 20% of the synaptic input to the LGN is retinal in origin. The majority of the afferent neurons is extraretinal, predominantly cortical, midbrain, and brain stem, thereby providing an anatomical framework in which M- and P-ganglion cell information from the retina en route to visual cortex is influenced significantly by non-visual inputs.[11] For example, afferent fibers to the LGN from the brain stem reticular formation appear to have a global effect that switches attention *between* sensory systems, such as blocking out extraneous sounds when reading. Input from the thalamus, superior colliculus, and the visual cortex found in geniculate circuitry can affect attentional processes within the visual domain.[12] LGN cells also have been shown to respond to some auditory and somatosensory stimuli, and several studies have confirmed that LGN responses are depressed by saccadic eye movements.[13] The literature on the microcircuitry of the LGN is extremely complex; only when the influences of these and other afferent connections are more completely understood will we have a comprehensive understanding of the functions of the LGN.[14]

Visual Cortex (Striate and Peristriate Areas)

The primary visual cortex (also known as Brodman's area 17) is located in the occipital lobe. The profuse neuron input from the dLGN gives layer IV of the visual cortex the appearance of a stripe, thus the term "striate area." Upon entering the visual cortex, the P- and M-cells remain segregated in different tiers of layer IV that serve to maintain their functional segregation. In area 18, lateralization takes place. Reading and language are predominantly in the left (dominant) hemisphere, while spatial relations and non-language functions are located in the right (non-dominant) hemisphere. They emerge as two major streams from area 18, the P-cells diverging to the inferior temporal cortex and the M-cells proceed, via the middle temporal (MT) area, to the visually responsive posterior parietal (PP) cortex. Of special interest is the manner in which the striate and the extrastriate areas interact to form a single extended visual system.

Extrastriate Cortex

Beyond area 18, the M-cell channel communicates with the middle temporal (MT) area. This cortical area manifests a number of attention-related response sensitivities, including direction, orientation, binocular interactions, analysis and perception of motion and apparent motion, smooth pursuit eye movements, and depth of objects. These connections reinforce the notion that individuals with SRD are likely to show deficits in visual perceptual functions supported by these areas.[15,16] Thus, the "motion" pathway information enters the parietal visual system from the MT area. The PP cortex is involved in the perception of spatial relations of objects in the visual field.[17] Since the PP cortex is connected with the frontal eye fields (Brodman's area 8) in the pre-motor area of the frontal cortex where voluntary saccadic movements are initiated,[14,18] it also serves as an integrating bridge between sensory and motor systems. In general, the M-cell stream is supported functionally by the right hemisphere that is more involved in global processing of low spatial frequencies. These characteristics are usually attributed to transient visual processing which is discussed below.

P-cell functioning is identified with the analysis of shapes, colors and textures. As was the case with the M-cells, responses are gated by attentional, behavioral, and situational variables. Studies of the right inferotemporal (IT) region of the cortex[19] that is involved exclusively in visual functions, have revealed P-cell sensitivity to visual discrimination learning, recognition, associative memory, fine stereopsis, and remembering an object's qualities. IT connections with the amygdala and hippocampus support the position that the limbal system is involved in visual recall, memory and learning.[20] P-cell channels are generally associated with sustained visual processing. To the extent that sustained processing is governed by its sensitivity to high spatial frequencies and foveal vision, both necessary characteristics of reading, it is reasonable to associate P-cell processing predominantly, but not exclusively, with left hemisphere functions.

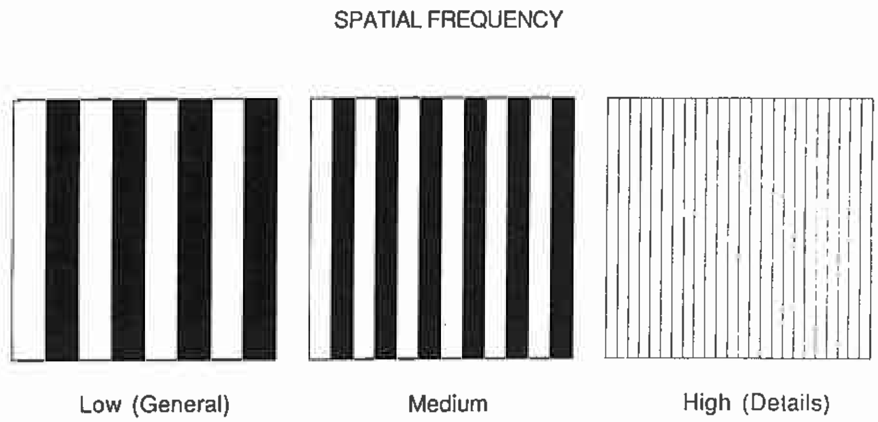

Figure 1. Examples of sine-wave gratings commonly used in vision research concerned with spatial frequency channels. Low spatial frequencies are shown on the left and high spatial frequencies on the right.

TABLE 1
CHARACTERISTICS OF TRANSIENT AND SUSTAINED SUBSYSTEMS

Transient	Sustained
1. Most sensitive to low and middle spatial frequencies: large overall shapes.	1. Most sensitive to high spatial frequencies: fine detail.
2. High sensitivity to contrast.	2. Low sensitivity to contrast.
3. Peripheral vision dominant.	3. Central (foveal) vision dominant.
4. Responds to onset and offset of stimulus. Short response persistence (transient).	4. Responds during and after stimulus presentation. Longer response persistence.
5. Most sensitive to high temporal frequencies.	5. Most sensitive to low temporal frequencies.
6. Responds to quickly moving targets (early warning).	6. Sensitive to stationary or slowly moving targets.
7. Sensitive to short wavelengths (e.g., blue).	7. Sensitive to longer wavelengths (e.g., red).
8. Global analysis of incoming visual information.	8. Identification of shapes and patterns.
9. Involved in perception of depth, flicker, motion, brightness discrimination.	9. Involved in processing color information.
10. Prepares visual system for the input of slower detailed information that follows.	10. Responds subsequent to transient output and is dependent upon transient output.

Characteristics of the Dual Processing System

From this brief review of the nature of the visual pathways from the retina to the cerebral cortex, it is apparent that retinal images are sampled at least twice by the visual system, but not in a redundant manner. First, global, coarse form information is sampled by quickly analyzing the low spatial frequency (LSF) content of retinal images in the M-cell channel. Then, the retinal images are sampled for fine (local) detail by processing the higher spatial frequencies in the P-cell channel (see Figure 1). The global-to-local mode of visual processing is mediated by the M- and P-cell channels: from the presence and location of the stimulus (M-cell) to the processing of fine detail (P-cell). In reading, for example, first, word shape and size are sampled globally in the field to the right of the fixation point prior to executing a saccadic movement. Then the succeeding foveation takes place for the processing of detail. Therefore, the temporal order of visual information flow along the retino-geniculo-cortical pathways is important. *Any alteration of the normal order and timing of the relative contributions or processing speed of the M- and P-cell pathways can result in a visual deficit.* Breitmeyer suggests that this interaction between M- and P-cells normally takes place in the higher visual centers.[21]

Prior to discussing the role of dual processing in reading, it is productive to review the interactions between transient and sustained processing. The former are low spatial frequency channels that elicit faster visual responses than high spatial frequency sustained channels (see Table 1). The transient system is more sensitive to temporally modulated or moving stimuli than sustained channels which are more receptive to stationary patterns and the resolution of fine detail. For a given spatial frequency stimulus, response is faster and more transient (less persistent) when motion is being detected than when pattern is being detected.[22] The two visual subsystems are separate but interactive. They respond differently to various spatial and temporal frequencies.

Specifically, the transient or magnocellular system is a fast operating system that is most sensitive to low and middle spatial frequencies and high temporal resolution. It responds to quickly moving targets, albeit for a short time. Therefore, the transient system has a short response persistence and short latency period. It serves as a pre-attentive "early warning" system by virtue of its sensitivity to motion and performs a global analysis of incoming visual information. It is involved in the control of eye movements, the localization of targets in space, and perception of depth. The rate of neural processing increases as contrast decreases, and when the wavelength of light is short. Blue filters accommodate both of these conditions. Finally, the transient system prepares the visual system for input to the slower, detailed oriented information processing system that follows.

The sustained system, on the other hand, responds more slowly than the transient system and is most sensitive to high spatial frequencies. Therefore, it has a primary role in the identification of shape of patterns and the resolution of fine detail. Its longer response persistence (duration) plays a significant role in visual processing. Unlike transient processing, P-cells are more sensitive to stationary or slowly moving targets and low temporal frequencies. The sustained system is involved in processing color information, and activity increases when the wavelength of light is long (red). The sustained system requires high contrast. If blurring is introduced (e.g., using a frosted acetate overlay), contrast of very high frequencies may be reduced to zero, thereby delaying the sustained activity, a point that we shall return to subsequently. *That the sustained system responds subsequent to transient output and is dependent upon transient output is very important*

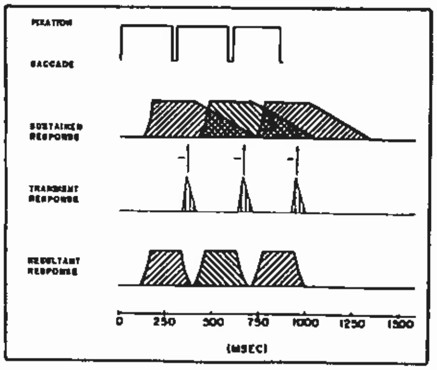

Figure 2. A hypothetical response sequence of sustained and transient channels during three 250 msec fixation intervals separated by 25 msec saccades (Panel 1). Panel 2 illustrates persistence of sustained channels acting as a forward mask from preceding to succeeding fixation intervals. Panel 3 shows the activation of the transient channels shortly after each saccade which exerts inhibition (arrows with minus signs) on the trailing, persisting sustained activity generated in prior fixation intervals. Panel 4 shows the resultant sustained channel response after the effects of the transient-on-sustained inhibition have been taken into account. (From "Unmasking Visual Masking: A Look at the 'Why' behind the Veil of the 'How'," by B. G. Breitmeyer, Psychological Review, 1980; 82: 52-59, Copyright 1980, American Psychological Association. Reprinted with permission.)

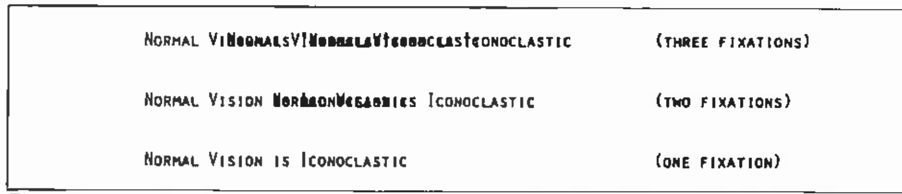

Figure 3. The perceptual masking effects of temporal integration of persisting sustained activity from preceding fixation intervals with sustained activity generated in succeeding ones when the reading of a printed sentence requires one, two or three fixations. Here, as in Panel 2 of Figure 2, the effects of transient-on-sustained inhibition have not been taken into account. (From "Unmasking Visual Masking: A Look at the 'Why' behind the Veil of the 'How'," by B. G. Breitmeyer, Psychological Review, 1980; 82: 52-69. Copyright, 1980, American Psychological Association. Reprinted with permission.)

in reading. Although some of the fine details of parallel processing remain unclear, the transient-sustained interaction appears to be critical in the facilitation of normal reading. For an overview of their processing characteristics, see Table 1.

Mechanism of Processing in Reading

The hypothesis is that the reading process depends upon the precise synchronization of the transient and sustained systems. Normal reading is a dynamic visual processing task that requires a succession of saccadic eye movements from one fixation to the next.

The slower sustained system is activated during fixations and extracts the details of the text. Since the sustained has a much longer visual response persistence than the transient channel, the duration of the response may outlast the duration of the stimulus. The rapid saccade fixation pattern, repeated throughout the reading period, activates the transient channels which are very sensitive to stimulus movements across the retina.[23] The stimulation of the transient system produced by a saccade then inhibits (suppresses) the visible persistence of the sustained system from the previous fixation. When the timing is perfect, the effect of the transient on the sustained system is to erase the pattern information and, thereby, prevents the "trailing persistence" of the preceding sustained pattern from interfering with the detailed information analyzed in the subsequent fixation. This response sequence is illustrated in Figure 2. Clear vision is maintained in each fixation as a result of the interaction between transient and sustained channels. The information encoded in a series of fixations is separated: letters and words do not overlap from one fixation to the next, consequently facilitating normal reading. Experimental support for this sequence of events is abundantly described in recent studies that involve transient system deficits.[15,24] In each fixation the average span of recognition is five or six characters, equivalent to 1.33 to 1.50 words. A high school student who reads 300 words per minute, or 100 words in 20 seconds, would make about 80 fixations per 100 words. One fixation, therefore, would equal 250 msec (20/80 = .25).[25] This value approximates Breitmeyer's interval in Figure 2.

The Effect of Poor Timing

A defect in the timing of either the transient or sustained system may interfere with reading, but it should be noted that transient system deficits have been identified as the principal offender. If the timing of the two systems is not synchronized appropriately to form a complete visual perception, the sustained visual activity generated in a previous fixation could persist and interfere with the sustained activity generated during the following fixation. A deficit that affects the timing of either system interferes with the processing of the second fixation since this could lead to superimposition of successive inputs. The reading process is impeded since the preceding pattern is not erased, and the overlapping of the two successive patterns produces a smeared image (see Figure 3). This outcome, attributed to a sluggish transient system response that fails to suppress the persistent sustained response, may be thought of as a form of "noise" in the system. Visual processing differences between normal and disabled readers are evident *when transient system processing is involved, but fail to surface under sustained processing conditions.*[26] Current research[1] indicates that the majority of children with SRD have a deficient transient system. It is of special interest to the optometrist that reading disability is the consequence of a deficit in the low spatial frequencies system (transient channels). Virtually all optometric and other research on reading has been focused on high spatial frequency stimuli, but rarely has involved low spatial frequencies.

By combining the results of several visual response persistence experiments, Lovegrove et al[10] accumulated data from 61 children with SRD and 61 controls (ages 7-13) and obtained some widely quoted statistics: 75.4% of the children with SRD, but just 8% of the controls, showed a transient system deficit. To be categorized as SRD, a subject had to demonstrate a reading lag of 2.5 years. This corresponds to approximately the 16th percentile. All of the SRD subjects met the normally accepted criteria, including average or better non-verbal intelligence, as described previously.

There is not sufficient data at this time to speculate on the types of reading errors that would most likely be associated with a transient deficit. One could surmise, however, that they probably would be visual rather than phonological, although both could be present in one individual.

Potential Treatments

The premise is that the primary visual problem of disabled readers is a transient system deficit that manifests itself as a less than optimal temporal relationship between transient and sustained processing. The product of this asynchrony is a lack of separation of successive stimuli from one fixation to the next. Therefore, interventions designed to either increase the rate of transient processing or delay sustained processing should compensate for the visual deficits of disabled readers and therefore improve reading performance. Let us examine examples of these two procedures in more detail.

1. The first study[27] involves visual search which closely approximates reading. A system of image blurring to degrade the printed characters was accomplished by using a frosted acetate overlay. This method degraded the printed characters and reduced the contrast at the high spatial frequency range of the stimuli, thus delaying the sustained response. The visual performance differences of three groups, normally achieving children (8-10 years), disabled readers (8-10 years), and a small number of adults were compared. All of the subjects had normal visual acuity. Each of the eight stimulus arrays consisted of a column of uppercase letters. Each column contained 18 rows of six letters per row. The column in each array contained either angular letters (e.g., E, M, X) or circular letters (e.g., R, G, O). Embedded within each column was a single angular target letter (e.g., Z) that appears randomly in one of the sets of six letters. The time to locate the target letter was compared for the three subject groups when the images in each column were sharp and slightly blurred by the acetate overlay. Position in the array was also a variable. Sharp images and blurred images were run blocked, albeit counterbalanced.

Visual search time for poor readers to locate the letter Z significantly improved when the visual arrays of uppercase letters were presented slightly out of focus ($p<0.001$). Visual performance differences between good and poor readers appeared to be associated with a sensory deficit that involved activity of high frequency spatial channels. Although the sluggish transient system response associated with poor readers was not directly remediated, this procedure reestablished the temporal precedence of transient system information by delaying the sustained response. The search time for good readers also decreased with the overlay, albeit slightly. The study is important because the stimuli approximated reading. The desired temporal relationship between transient-to- sustained processing that was attained resulted in an improved perceptual performance of poor readers that approached normal levels. We plan to repeat this experiment using shortwave blue filters instead of frosted acetate overlays in order to increase the rate of transient processing (see Table 1, #7). This strategy is expected to synchronize the transient-on-sustained interaction and yield similar results that will lend further support to the hypothesis that visual deficits in the transient system may be interfering with reading performance.

2. The second study is directly concerned with improving reading. Williams, LeCluyse, and Rock-Faucheux[1] conducted the research with 32 normal and 38 disabled readers, ages 8 to 12 years. They demonstrated that reading achievement in disabled readers could be improved by varying wavelength, luminance, or with image-blurring. As noted earlier, the rate of transient processing increases when the wavelength of light is short (blue). By placing a blue acetate transparency over the white letters on a computer monitor, they obtained statistically significant improvement ($p<0.05$) in reading comprehension using a reading selection that was appropriate for the child. Further, compared to the no filter condition, a blue acetate transparency placed over the print in a book was equally effective in synchronizing the transient-sustained interaction when a transient system deficit existed. Image blurring with frosted acetate that degraded the contrast of the printed characters also had a significant effect on reading comprehension by delaying the sustained response. They proposed that the relationship between the transient and sustained systems is important in reading because the transient system directs the eye to the location of the words on a page, and the slower sustained system extracts the details of the letters. Therefore, they expected that intervention designed to either increase the rate of transient processing or delay the sustained processing would compensate for the transient visual deficit. Either would eliminate the deficit in timing and improve reading performance *in disabled but not normal readers.* Since imposing a color on a visual display by wearing colored lenses or using color overlays reduces the luminance on the display, white, light gray (20% reduction), and dark gray (50% reduction) filters also were used to provide a measure of the effects of reducing luminance independent of color and without sacrificing image clarity. The light gray, but not the dark gray, was equally effective as the blue with both computer monitors and books indicating that luminance as well as wavelength affects performance.

Finally, the authors report that approximately 70% of SRDs have transient system deficits. Approximately 80% of the experimental group responded to the interventions described.

Conclusions and Recommendations

Current research appears to support the hypotheses of Breitmeyer, Lovegrove, and others that reading-disabled individuals differ from normally achieving readers in the visual functioning of their transient but not their sustained systems.[10,15] That is, as the processing task becomes more dependent on the activity of the transient system, the performance of disabled readers, but not normal readers, deteriorates.[28] Regular testing of transient and sustained visual processing ultimately may add another dimension to the overall optometric assessment of children identified as reading-disabled. Although the current experimental evidence that supports the existence of these visual deficits is encouraging, I am not suggesting a return to a unitary deficit hypothesis, as was proposed in Vellutino's language deficit theory.[29] For example, the validity of contrast sensitivity at age 6 years to predict reading ability at age 8, after correction for IQ, is $r = 0.34$ ($p<0.01$).[10] The percent of variance (r^2), however, is a not very meaningful 11%. Although statistically significant, it is not clinically consequential. These results tell us that factors other than contrast sensitivity, such as visual perceptual, visual-motor, and other visual functional deficits, may contribute to the remaining 89% of the total variance.

Unlike many of the tests used by experimental psychologists and optometrists, the visual functioning that has been discussed is not based primarily upon detail and high spatial frequency stimuli. In contrast, experimental results indicate that transient deficits are almost devoid of perceptual mechanisms and cognitive factors, some of which are well beyond the visual system.[10] The experimental evidence, nevertheless, tends to confirm Livingstone's conclusion that at least a subset of SRD subjects, in particular those with visual disturbances, will show defects in visual functions carried by the magnocellular (transient) pathway.[30]

The therapeutic approaches described earlier were designed to compensate for the transient system deficits. I am hopeful that we will be able to replicate the research. Although manipulation of the variables appears to be effective in improving certain reading skills (as defined by the experimenters), the best interest of the patients will be realized if optometric researchers were to develop a therapeutic regimen that would increase the rate of transient processing without the need for filters and overlays. I agree with Garzia and Nicholson[31] that we must identify specific vision therapy procedures from those currently in use and/or develop new strategies that will impact on transient and sustained processing. For example, the research of Williams and Bologna[6] has demonstrated that reading development in at least some poor readers has been arrested at the pre-attentive, holistic stage, rather than continuing to the analytical processing level. These poor readers would benefit from vision therapy that stresses more detailed visual discrimination, analysis, and synthesis to develop the focal attentive system. This change in processing strategy would encourage the development of selective attention and facilitate the rapid perception of detailed information, as in words.

We have the advantage of being able to cross-validate the outcome of our therapy, case by case, with the procedures established by the research that has been reported. Establishing synchronization of the transient and sustained systems, as illustrated in Figure 2, prior to visual perceptual and processing therapy would provide the optometrist with an important baseline measurement when treating children who have been identified as reading- and learning-disabled. This comprehensive strategy would involve the integration of a molecular with a global performance-oriented intervention approach for both diagnosis and therapy. It also raises many questions. For example, is it possible that developing increased saccadic accuracy and speed would have a salutary effect on a transient deficit? To what extent is transient and sustained processing related to successive and simultaneous processing? The improved prognosis accompanying these combined modes of therapy could provide further evidence that visual processing is, indeed, an important correlate in the complex of variables related to reading achievement.[32]

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References

1. Williams MC, LeCluyse K, Rock-Faucheux A. Effective interventions for reading disability. J Am Optom Assoc, 1992; 63 (6): 411-17.
2. Grisham JD, Simons HD. Refractive error and the reading process: a literature analysis. J Amer Optom Assoc, 1986; 57 (1): 44-55.
3. Simons HD, Grisham JD. Binocular anomalies and reading problems. J Am Optom Assoc, 1987; 58 (7): 578-587.
4. Suchoff IB. Research on the relationship between reading and vision--what does it mean? J Learn Disabil, 1981; 14 (10): 573- 576.
5. Critchley M. The dyslexic child. London: Heinemann, 1970.
6. Williams MC, Bologna NB. Perceptual grouping in good and poor readers. Percept Psychophysics, 1985; 38 (4): 367-374.
7. Solan HA. A comparison of the influences of verbal-successive and spatial-simultaneous factors on achieving readers in fourth and fifth grade: a multivariate correlational study. J Learn Disabil, 1987; 20 (4): 237-242.
8. Vernon MD. Varieties of deficiency in the reading processes. Harvard Educ Review, 1977; 47 (3): 396-410.
9. Williams MC, Lecluyse K. Perceptual consequences of a temporal processing deficit in reading-disabled children. J Am Optom Assn, 1990; 61 (2): 111-121.
10. Lovegrove WJ, Martin F, Slaghuis W. A theoretical and experimental case for a visual deficit in specific reading disability. Cognitive Neuropsych, 1986; 3: 225-267.
11. Bassi CJ, Lehmkuhle S. Clinical implications of parallel visual pathways. J Am Optom Assn, 1990; 61 (2): 98-110.
12. Sherman SM, Koch C. The control of retinogeniculate transmission in the mammalian lateral geniculate nucleus. Experimental Brain Research, 1986; 63: 1-20.
13. Noda H. Depression in the excitability of relay cells of the lateral geniculate nucleus following saccadic eye movements. J Physiol (London), 1977; 249: 87-102.
14. Casagrande VA, Norton TT. Lateral geniculate nucleus: a review of its physiology and function. In: Leventhal AG (Ed.) The neural basis of visual function. Vision and visual dysfunction, Volume 4. Boca Raton, FL: CRC Press, 1991: 41-84.
15. Breitmeyer BG. The role of sustained (P) and transient (T) channels in reading and reading disability. In: Wright SF, Groner R. (Eds.). Facets of dyslexia and its remediation. Amsterdam: Elsevier Science Publishing, 1993: 13-31.
16. Motter BC. Beyond extrastriate cortex: the parietal visual system. In: Leventhal AG (Ed.). The neural basis of visual function. Vision and visual dysfunction, Volume 4. Boca Raton, FL: CRC Press, 1991: 371-387.
17. Mishkin M. Cortical visual areas and their interconnections. In: Karczmar AG, Eccles JC (Eds.). Brain and human behavior. Berlin: Springer-Verlog, 1992.
18. Garzia RP, Sesma M. Vision and reading I: neuroanatomy and electrophysiology. J Optom Vis Develop, Spring 1993; 24 (1): 4-51.
19. Gross LG. Visual function of inferotemporal cortex. In: Jung R (Ed.). Handbook of sensory physiology, Vol. VII (3B), Ch. 23. Berlin: Springer-Verlag.
20. Rolls ET. Neural organization of higher visual functions. Current Opinion Neurobiology, 1991; 1: 274-278.
21. Breitmeyer BG. Parallel processing in human vision: history, review, and critique. In: Brannan JR (Ed.). Applications of parallel processing in vision. New York: Elsevier Science Publishing Co., 1992: 37-78.
22. Williams MC, Lovegrove W. Sensory and perceptual processing in reading disability. In: Brannan JR (Ed.) Applications of parallel processing in vision. New York: Elsevier Science Publishing Co., 1992: 263-302.
23. Lovegrove W. Do dyslexics have a visual deficit? In: Wright SF, Groner R (Eds.). Facets of dyslexia and its remediation. Amsterdam: North Holland, 1993: 33-49.
24. Williams MC, Breitmeyer BG, Lovegrove WJ, Gutierrez C. Metacontrast with masks varying in spatial frequency and wavelength. Vision Research, 1991; 31 (11): 2017-2023.
25. Solan HA. Eye movement problems in achieving readers: an update. Am J Optom Physiol Optics, 1985; 61 (12): 812-819.
26. Rock-Faucheux A, LeCluyse K, Williams M. The effects of wavelength on visual processing and reading performance in normal and disabled readers. In: Wright SF, Groner R (Eds.). Facets of dyslexia and its remediation. Amsterdam: Elsevier Science Publishers, 1993: 77-94.
27. Williams MC, Brannan JR, Lartigue EK. Visual search in good and poor readers. Clin Vis Sci, 1987; 1 (4): 367371.
28. Williams MC, Molinet K, LeCluyse K. Visual masking as a measure of temporal processing in normal and disabled readers. Clinic Vis Sci, 1989; 4 (2): 137-144.
29. Vellutino FR. Dyslexia: theory and research. Cambridge, MA: The MIT Press, 1979.
30. Livingstone M. Parallel processing in the visual system and the brain. Is one subsystem selectively affected in dyslexia? In: Galaburda AM (Ed.). Dyslexia and development. Cambridge, Ma: Harvard University Press, 1993: 237-256.
31. Garzia RP, Nicholson SB. Visual function and reading disability: an optometric viewpoint. J Am Optom Assoc, 1990; 61 (2): 88-97.
32. Kavale K. Meta-analysis of the relationship between visual perceptual skills and reading achievement. J Learn Disabil, 1982; 15 (1): 42-51.

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