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Low level visual and auditory processing in dyslexic readers

Bedi, Gail C., Ph.D.

City University of New York, 1994

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LOW LEVEL VISUAL AND AUDITORY PROCESSING
IN DYSLEXIC READERS

by

GAIL C. BEDI

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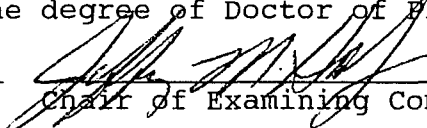
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Abstract

LOW LEVEL AUDITORY AND VISUAL PROCESSING
IN DYSLEXIC READERS

by

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The perceptual deficit hypothesis of dyslexia states that the difficulties dyslexic children encounter in learning to read are related to deficits in perceptual processing. Most investigations of this hypothesis have focussed upon either auditory or visual processing. This approach fosters the conception of dyslexia as a unitary disorder caused by one or the other perceptual deficit. This study examined both auditory and visual processing in dyslexic children. Twenty-nine dyslexics, 49 chronologically-age-matched normal readers (CA controls) and 17 younger normal readers who had the same absolute reading ability as the dyslexics (RA controls) were administered a battery of three auditory perception tests and three visual perception tests. These tests were designed to assess discrimination, temporal order and closure in each sensory modality. They were also administered a test of single word spelling. It was expected that dyslexics would be impaired in auditory and visual processing relative to both CA and RA controls. Further, it was expected that it would be possible to subgroup dyslexic children on the basis of their

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having auditory and/or visual processing deficits and that each of these subgroups would be associated with distinct strengths and weaknesses on the spelling test of the Boder Test of Reading-Spelling Patterns. Results of this study did not support the perceptual deficit hypothesis of dyslexia. Dyslexics could not be discriminated from CA or RA controls on the basis of their performance on auditory and/or visual processing tests. Further, subgroups of dyslexics, based upon the presence or absence of auditory and/or visual processing deficits, were not significantly different from each other in their pattern of spelling errors. However, dyslexics were found to have a deficit in processing temporal order information, regardless of the modality of presentation. Further, dyslexics who were impaired in temporal order processing within both the auditory and visual modalities performed significantly below dyslexics who had no impairment in either auditory or visual temporal order processing on a measure presumed to assess the ability to employ phonics in spelling. Thus, it appears that impaired temporal order processing plays a role in dyslexia irrespective of sensory modality.

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LOW LEVEL AUDITORY AND VISUAL PROCESSING
IN DYSLEXIC READERS

The legal definition of a learning disability is "a disorder in one or more of the basic psychological processes involved in understanding or using language, spoken or written, which may manifest itself in an imperfect ability to listen, think, speak, read, write, spell, or do mathematical calculations." (Public Law 94-142, 1975). The perceptual deficit hypothesis of learning disabilities suggests that the difficulties learning disabled (LD) children encounter in learning to read are related to impaired perceptual processing skills (Bryant & Bradley, 1983). This hypothesis is implied in the legal definition, and it has become a core concept in the clinical diagnosis of learning disabilities (Wong, 1986). In addition, the perceptual deficit hypothesis is reflected in several learning disabilities classification systems; dyslexic children (children who have a learning disability in reading) have been grouped according to demonstrated or presumed deficits in visual processing, auditory processing or both (Boder, 1973; Johnson & Myklebust, 1967; Mattis, French & Rapin, 1975).

While the perceptual deficit hypothesis has been an explicit and implicit part of the definition and diagnosis of learning disabilities, there exists a great deal of variation among researchers in terms of whether defective

auditory processing (Bryant & Bradley, 1983; Wagner & Torgesen, 1987) or defective visual processing (Lovegrove, Martin & Slaghuis, 1986; May, Williams & Dunlap, 1988; Soloman & May, 1990) is the root of the dyslexic child's lack of proficiency in reading. Significantly fewer studies have explored whether or not both auditory and visual processing are impaired in these children. Further, this predominant focus upon a disturbance in one modality, rather than a disturbance in both modalities, has fostered a conception of dyslexia as a homogeneous, or unitary disorder rather than a heterogeneous disorder.

There are yet other issues impeding the investigation of visual and auditory processing as etiologic determinants of dyslexia. One of these issues is that there has been little consistency among researchers as to how dyslexia should be operationally defined. The study of learning disabilities has been plagued by controversy about how to define the disorder ever since the term was first introduced (Hooper & Willis, 1989; Wong, 1986). In attempts to operationalize the definition of learning disabilities, it was proposed that there must be a discrepancy between the child's intellectual ability and his/her level of achievement (Hooper & Willis, 1989; Wong, 1986). However, there has been no consensus about the amount of discrepancy needed for diagnosis of LD, nor about how to measure this discrepancy (Hooper & Willis, 1989; Wong, 1986). Further,

while discrepancy criteria were accepted by some as necessary for the diagnosis of learning disabilities (Heath & Kush, 1991)), they have been rejected by others (Morrison & Siegel, 1991; Senf, 1986). Because of this controversy, researchers have employed a wide range of index groups. While some researchers administered reading achievement and IQ tests to document a discrepancy between achievement and intellectual potential (Elliott et al., 1990; Snowling et al., 1986; Tallal, 1980), others administered only reading achievement or IQ tests (Flynn & Deering, 1989; Reed, 1989). The identification of index groups was even less rigorous for those researchers who assumed that the children they studied were LD because they had been selected from schools, camps or programs for LD or dyslexic children (Hardy, McIntyre, Brown & North, 1989; Flynn & Deering, 1989; Snowling et al., 1986; Tallal, 1980). Just as various researchers have employed varying criteria to define their index groups, they have employed a wide variety of labels: learning disabled, reading impaired and dyslexic. For clarity, all of these groups will be labeled "dyslexic" in the following literature review and in body of this paper.

The majority of these investigations have not shed light upon whether deficits in auditory and/or visual processing are causally related to deficits in reading (Bryant & Bradley, 1983). The possibility that the weaknesses in auditory processing or visual processing

exhibited by dyslexic children are the result rather than the cause of not having learned to read must be considered (Bryant & Bradley, 1983). Bryant and Bradley (1983) have suggested that this causal question could be better addressed if investigators used two control groups, chronological-age-matched (CA controls) and reading-ability-matched controls (younger normal readers who are reading at the same achievement level as the dyslexic children) (RA controls), rather than just the CA controls.

This is Bryant and Bradley's (1983) rationale for using two such control groups. If dyslexics are found to have a perceptual processing deficit relative to the CA control group only, there are at least two possible interpretations of the results. The perceptual processing deficit caused the reading impairment or lack of acquisition of reading skills resulted in a perceptual processing deficit. Comparing the dyslexics to another group of normal readers who are reading at the same absolute level as the dyslexics, excludes the possibility that lack of reading ability caused the perceptual processing deficit, if dyslexics are found to have a perceptual processing deficit relative to both CA controls and RA controls. However, if the dyslexics are found to have a perceptual processing deficit relative to the CA controls, but not RA controls, interpretation of the results is again murky. Such a result could indicate that dyslexics are developmentally delayed in the acquisition of

perceptual processing skills or that the development of perceptual processing skills is facilitated by the acquisition of reading skills.

The purpose of this study was to investigate whether research-identified dyslexic children could be distinguished from normal readers their same age (CA controls), as well as younger normal readers who were reading at the same absolute level as the dyslexics (RA controls) on the basis of auditory and/or visual processing deficits. A battery of visual processing and auditory processing tests was administered to a sample of dyslexic, elementary-school children, CA controls, and RA controls. The perceptual deficit hypothesis of dyslexia would be supported if the dyslexics had auditory and/or visual processing deficits relative to both RA and CA controls.

Further, whether or not dyslexia is a unitary disorder was explored. It was hypothesized that, if dyslexia is not a unitary disorder, it would be possible to subgroup dyslexics on the basis of auditory and/or visual processing deficits. Further, these subgroups would be associated with distinct strengths and weaknesses on an assessment of literacy skills (single word spelling test) which was distinct from the assessment upon which the dyslexics were initially identified (single word reading test). On the other hand, if dyslexia is a unitary disorder, all dyslexic children would have the same pattern of processing deficits

(auditory and/or visual) or subgroups of dyslexics, derived on the basis of auditory and/or visual processing deficits, would have similar correlates with regard to their performance on the spelling test.

Background Information

The nature of the perceptual difficulty identified as the cause of dyslexia has changed over time. Orton (1928), through his description of dyslexic readers, was instrumental in focussing the attention of early researchers upon the relationship between impairments in visual perception and reading impairment (Hooper & Willis, 1989). The visual perception deficit explanation for dyslexia received less consideration as researchers determined that reading impairment could also be related to deficits in auditory processing (Bryant & Bradley, 1983), verbal mediation (Vellutino, 1977), attention (Dykman, Ackerman, Clements & Peters, 1971), memory (Brainerd & Reyna, 1991), and intersensory integration (Birch & Belmont, 1964). While the relationship between reading and a number of cognitive functions was investigated, most research efforts during this period focussed upon the examination of auditory processing in impaired readers. Recently, investigators have returned to the examination of visual processing deficits in impaired readers (Lovegrove, Martin and Slaghuis, 1986; Slaghuis and Lovegrove, 1985; May, Williams and Dunlap, 1988). However, unlike prior investigations of

visual processing in dyslexic readers, which examined higher level visual processing (i.e. visual perception of letters or words), much of this current research has examined low level visual processing (visual perception of non-verbal visual stimuli). By demonstrating that dyslexic children had low-level visual perception deficits, interest in visual processing deficits as a cause of dyslexia has been renewed. Accordingly, researchers have begun to apply these basic visual research findings in dyslexic readers toward investigations of complex visual processing believed to be more closely related to reading.

Current Research in Visual Processing in Dyslexics

Interest in visual processing deficits as the cause for dyslexia has been re-generated by the research of Lovegrove and his colleagues (1985, 1986, 1987, 1988). This research group investigated low level visual processing in dyslexics, relative to normal readers, within the theoretical framework of there being two parallel pathways or channels in visual processing. Investigations of the properties of these channels have been conducted, within the context of spatial frequency analysis, using a number of psychophysical strategies (Breitmeyer, Levi & Harwerth, 1981). Sine wave gratings are frequently used as stimuli in these investigations because the basic assumption behind spatial frequency analysis is Fourier's theorem that any two-dimensional stationary stimulus can be represented by

combining sine-wave gratings which vary in spatial frequency (width of the black bars in the grating), orientation (rotation of the grating to the right or left of vertical), and contrast (luminance difference between the light and dark bands of the grating) (Lovegrove, Martin, and Slaghuis, 1986). Figure 1 provides examples of sine wave gratings.

Spatial frequency is expressed in number of cycles (one dark plus one light bar) per degree of visual angle (c/deg) (Lovegrove et al., 1986). The sine wave grating to the right in Figure 1 has more black bars per degree of visual angle than the sine wave grating to the left. It, therefore, has a higher spatial frequency.

Contrast is expressed by the following function: $(L_{max} - L_{min}) / (L_{max} + L_{min})$ where L_{max} = the luminance of the most intense part of the white bars, and L_{min} = the luminance of the least intense part of the dark bars.

Temporal frequency, another characteristic of sine wave gratings, can be studied through the introduction of successive on-set and off-set of the sine wave grating or of the background luminance (flicker). High temporal frequency would be a rapid flicker or a short duration between stimulus on-set and off-set. Conversely, low temporal frequency would be a slow flicker or a long duration between stimulus on-set and off-set.

Lovegrove et al. (1986) reviewed and summarized research in which sine-wave gratings had been used in

psychophysical experiments to investigate visual processing in normal adults. They concluded that there was strong evidence for the existence of two distinct channels within the human visual system, the sustained system and the transient system, and that each system was characterized by its differential response to specific characteristics of visual stimuli. The sustained system preferentially responds to stimuli of high spatial frequency, low temporal frequency, low contrast, and long duration, which are presented to the central or foveal visual field. While the transient system responds optimally to low-spatial-frequency, high-temporal-frequency, high-contrast, short-duration stimuli located in the peripheral or parafoveal visual field. Based on these findings, different functions for each visual system were proposed: the sustained system was theorized to transmit information about non-moving patterns, and the transient system was thought to be a motion or flicker detection system which transmitted information about stimulus change.

Transient Visual System Functioning in Dyslexics and Normal Readers

Lovegrove and his colleagues (1985, 1986) postulated that dyslexics are impaired in transient visual system processing. They argued that previous visual processing experiments failed to differentiate between normal readers and dyslexics (Graveson & Standing, 1986; Vellutino et al.,

1975) because they employed static visual displays or visual memory tasks, and that in order to detect impaired visual processing in dyslexics, short duration stimuli and/or several successive presentations of visual stimuli should be employed. To examine transient visual system functions in dyslexics, they measured visual perception as a function of the manipulation of the various characteristics of sine-wave gratings (spatial frequency, contrast, orientation, temporal frequency).

As a basis for theorizing about how visual processing in dyslexics would be affected as a function of manipulating the various characteristics of sine-wave gratings, Lovegrove and his colleagues (1985, 1986) relied upon Breitmeyer's (1980) theory of functional interaction between the sustained and transient systems during visual processing.

Specifically, Breitmeyer (1980) theorized that the sustained and transient visual systems interact to produce clear pattern vision during each visual fixation. This interaction is represented in Figure 2, and was explained by Breitmeyer in the following manner. Activity in the sustained system is thought to be initiated when the eyes fixate upon a physical stimulus. However, this sustained system response can outlast the duration of the physical stimulus, and result in continued sustained-system response even though visual fixation is changed (an eye movement or saccade occurred). This continuation of response in the

absence of a physical stimulus accounts for the phenomena of visual persistence. It is the proposed function of the transient system to inhibit visual persistence. Breitmeyer thought that the transient system response, and thus, the inhibition of visual persistence, is initiated when a saccade occurs.

In summary, a sustained system response is initiated by fixation upon a physical stimulus. If this response persists, the phenomena of visual persistence occurs. Normally, visual persistence is inhibited by the transient system. This inhibitory transient system activity is initiated when an eye movement occurs in order to fixate upon a new visual stimulus. The result is clear pattern vision. Breitmeyer thought that without such interaction, when reading required several visual fixations, successive inputs would be superimposed upon each other.

Transient visual system processing as a function of spatial frequency.

Slaghuis and Lovegrove (1985) began to test their hypothesis about impaired transient system visual processing in dyslexics by replicating a study of Breitmeyer et al. (1981), in which adults showed increased duration of visual persistence as a function of increased spatial frequency of sine-wave gratings. Slaghuis and Lovegrove (1985) interpreted the results of Breitmeyer et al. (1981) within the context of the transient system inhibition upon the

sustained system theory. It was reasoned that, since the transient system responds most strongly to stimuli of low spatial frequencies, transient system inhibition upon the sustained system would be strongest for sine-wave gratings of low spatial frequency. Furthermore, as increasingly higher spatial frequency sine-wave gratings were used, the transient system would respond less strongly while the sustained system would respond more strongly. Consequently, as the spatial frequency of sine-wave gratings was increased, the inhibition of the transient system upon the sustained system decreased, causing longer duration of visual persistence. Slaghuis and Lovegrove (1985) wanted to determine if this finding could be generalized to children and further, if dyslexics could be differentiated from normal readers.

Slaghuis and Lovegrove (1985) measured the duration of visual persistence as a function of spatial frequency in dyslexic children and age-matched normal readers using a psychophysical procedure called the continuation of form technique. In this technique, a sine wave grating is alternated with a blank of the same size and luminance as the sine wave grating (grating - blank - grating), and the duration of the blank is varied until the child reports seeing a clear blank. The duration until the child reports seeing a clear blank was interpreted, within the context of Breitmeyer's transient-sustained interaction theory, as a

measure of visual persistence. The reading-disabled children had longer durations of visual persistence than the controls. They also showed less of an increase in visual persistence as a function of increased spatial frequency than did the normal readers, and this effect was more pronounced for stimuli of long duration, rather than short duration.

Lovegrove et al. (1986) proposed a two-component model of transient-sustained visual system interaction to explain these findings. They felt that the first component of transient-sustained interaction involved phasic inhibition as described by Breitmeyer (1980), while the second component involved tonic inhibition. Component 1 occurred for low-spatial-frequency or short-duration stimuli and component 2 occurred for high-spatial-frequency or long-duration stimuli. Transient system response in dyslexics would be impaired for both components. However, due to the different type of responding (phasic vs. tonic) within each component, the result would be different as spatial frequency or duration of stimuli increased.

Breitmeyer's (1980) model of transient-sustained interaction explains component 1 transient-sustained interaction and the phenomena of increased visual persistence when low-spatial-frequency or short-duration stimuli are used. This model was discussed above.

Lovegrove et al. (1986) offered the following explanation of component 2 transient-sustained visual system interaction. They theorized that tonic inhibition of sustained system response has the effect of slightly decreasing sustained system response in comparison to what the response would have been without such inhibition. If sustained system response is then increased by presenting high-spatial-frequency or long-duration stimuli, the result is increased visual persistence. The level of tonic inhibition from the transient visual system has not increased, but the level of response from the sustained system has, and it is uninhibited sustained system response which accounts for the phenomena of visual persistence. If dyslexics have impaired transient system functioning, they would start off with less tonic inhibition of the sustained system. In other words, for component 2 transient-sustained interaction, the dyslexics would have increased activity in the sustained system relative to controls. Thus, when stimuli of higher spatial frequency or longer duration were presented, dyslexics would show less of an increase in sustained system response, and therefore less of an increase in visual persistence, than would controls.

In contrast, Smith et al. (1986) failed to find evidence of a similar deficit in dyslexic readers. They investigated the duration of visual persistence as a function of spatial frequency in school-identified dyslexics

and age-matched, school-identified, normal readers. High and low spatial frequency sine-wave gratings were presented and reaction time for on-set and off-set of the stimuli was measured. Visual persistence was calculated as the difference between mean off-set and mean on-set reaction time for a sine-wave grating of a particular frequency. For both groups, on-set and off-set reaction times increased as spatial frequency increased.

Transient system visual processing as a function of contrast.

Slaghuis and Lovegrove (1985) investigated the duration of visual persistence as a function of contrast, again using the continuation of form technique. Within the context of Breitmeyer's theory of interaction between the sustained and transient visual channels, it was theorized that increasing contrast would decrease the duration of visual persistence as the transient system preferentially responds to stimuli of high contrast, and an enhanced transient system response would decrease the duration of visual persistence. They presented dyslexics and age-matched normal readers with low and high spatial frequency sine-wave gratings, and varied the level of contrast from low to high. For both dyslexics and normal readers, the duration of visual persistence for stimuli of both high and low spatial frequencies was shorter as stimulus contrast was increased. However, the dyslexic children showed significantly less of a decrease in the

duration of visual persistence as contrast was increased than did the control children. These results are consistent with Breitmeyer's interaction theory in that, if the transient system of the dyslexics was weaker, decrease in visual persistence as a function of increased contrast would be expected to be lower than in normal readers.

Transient system visual processing as a function of temporal frequency.

Martin and Lovegrove (1987) hypothesized that, if dyslexics had a deficit in the transient system, the proposed flicker-sensitive system, they would be less sensitive than normal readers to the perception of a flickering sine wave grating, and that the differences between dyslexics and normal readers would increase as temporal frequency increased because the transient system is maximally sensitive to stimuli of high temporal frequencies. They presented low spatial frequency sine-wave gratings at five rates of flicker, ranging from 5 to 25 Hz, to dyslexics and age-matched normal readers, using a modification of the method of constant limits (after two correct responses contrast was reduced but after one incorrect response contrast was increased). For both groups, threshold increased (sensitivity decreased) as temporal frequency increased. However, the dyslexics had higher thresholds overall than the controls, and this difference increased as temporal frequency increased.

Using the same procedure, Martin and Lovegrove (1987) then measured sensitivity to flickering sine wave gratings as the spatial frequency of sine-wave gratings was varied from low to high. Overall, the control subjects were more sensitive than the dyslexics to rapidly-flickering gratings. This difference between groups increased as the spatial frequency of the sine wave grating increased.

Martin and Lovegrove (1988) further investigated transient visual system deficit in dyslexics as a function of temporal frequency. This time they presented low- and high-spatial-frequency sine-wave gratings with a flickering (6 Hz) background luminance to the same sample of dyslexics and normal readers. The introduction of a flickering background luminance is believed to mask only gratings which are detected by the transient system (low spatial frequency) because the flicker desensitizes cells in the transient system, which are sensitive to sudden-onset and sudden-offset stimuli, but not cells in the sustained system which are pattern sensitive (Smith, Early & Grogan, 1986). Slaghuis and Lovegrove hypothesized that if dyslexics have a transient system deficit, the introduction of background flicker would have less of an effect upon their performance than upon the performance of the normal readers. They found that sensitivity decreased for the normal readers when background flicker was introduced for low-spatial-frequency sine wave gratings, but had no effect upon high-spatial-

frequency sine wave gratings. However, the reverse effect was found for the dyslexics; the introduction of background flicker had no effect when low-spatial-frequency gratings were used, but caused decreased sensitivity when high-spatial-frequency gratings were used. Thus, the expected differential effect of background flicker upon visual perception was found only for low-spatial frequency sine wave gratings.

Smith et al. (1986) also investigated the duration of visual persistence as a function of background flicker in dyslexics and age-matched normal readers. High and low spatial frequency sine-wave gratings were presented with background flicker, and reaction time for stimulus on-set and stimulus off-set was measured. Visual persistence was calculated as the difference between mean off-set and mean on-set reaction time for a sine-wave grating of a particular frequency. While the dyslexics consistently had longer reaction times than the normal readers this difference was not significant.

Sustained Visual System Functioning in Dyslexics and Normal Readers

Lovegrove et al. (1986) also conducted psychophysical experiments which were presumed to assess functioning in only the sustained visual system. They hypothesized that if the visual system deficit of dyslexics was specific to the transient system, there would be no differences between

dyslexics and normal readers on tasks which assessed sustained system functioning.

Lovegrove et al. (1986) compared the performance of normal and dyslexic children on direction tilt illusion experiments. Specifically, in this illusion, a vertically-oriented sine-wave grating is superimposed upon another vertically-oriented sine-wave grating (surround grating). If the orientation of the surround sine-wave grating is 20-30 degrees from vertical and the superimposed sine-wave grating continues to be vertically oriented, the superimposed grating appears to be tilted away from the surround sine-wave grating. If the orientation of the surround sine-wave grating is oriented 60 - 75 degrees from vertical, then the vertically-oriented, superimposed sine-wave grating appears to be tilted towards the surround sine-wave grating (Lovegrove et al., 1986). A sine-wave grating was superimposed upon surround sine-wave gratings whose orientations ranged from 10 to 92 degrees, clockwise or counter-clockwise. No differences in perceiving the illusions were found between the two groups. These results were interpreted as indicating that there were no differences in the breadth of orientation tuning bandwidths, a purported sustained system process, between the normal and dyslexics.

Bandwidth of spatial frequency channels in the visual systems have been psychophysically investigated using the

selective adaptation technique (Lovegrove et al. 1986). This technique measures threshold change when the viewing of one sine-wave grating is preceded by viewing another sine-wave grating (Lovegrove et al., 1986). In previous research, maximum increase in threshold was found when the two sine-wave gratings were of the same spatial frequency (Lovegrove et al., 1986). In this experiment, Lovegrove et al. (1986) presented dyslexics and age-matched normal readers with a low spatial frequency sine-wave grating (the spatial frequency at which previous experiments had demonstrated that dyslexic children were less sensitive to change in contrast threshold as a function of spatial frequency, and had longer visual persistence) for inspection and then presented a second sine-wave grating, with spatial frequency ranging from low to high, for inspection. Both groups showed similar changes in threshold as the spatial frequency of the second sine-wave grating was varied. These results were interpreted as indicating that the two groups did not differ in the breadth of channel spatial frequency bandwidths, another sustained system function.

Lovegrove et al. (1986) also investigated the oblique effect in dyslexics and normal readers. Visual perception research in adults had previously demonstrated that stronger performance was obtained when vertical or horizontally oriented sine-wave gratings rather than obliquely-oriented sine-wave gratings were used (Lovegrove et al., 1986).

Because this effect was found for high-spatial-frequency stimuli, but not for low-spatial frequency stimuli and because the effect was stronger for sine-wave gratings presented foveally rather than peripherally, it was assumed that the oblique effect reflected sustained channel functioning (Lovegrove et al., 1986). Lovegrove et al. (1986) compared contrast threshold, in dyslexics and age-matched normal readers, for low- and high-spatial-frequency sine wave gratings, which were presented in vertical or 45 degree oblique orientation. The groups differed in contrast threshold as spatial frequency increased but they did not differ in the magnitude of the oblique effect. These results were interpreted as indicating that the groups differed in transient system functioning but not in sustained system response.

In summary, while there are findings to the contrary (Smith et al, 1986), the work of Lovegrove and his colleagues (1985, 1986, 1987, 1988) suggests that there is a specific transient system deficit in the visual systems of dyslexics. To review, the transient system is characterized by strongest responding to low-spatial-frequency, high-temporal-frequency, short-duration stimuli and it is thought to be a flicker or motion detection system which transmits information about stimulus change. Further, it has been theorized that one of the roles of the transient system is to inhibit sustained system response when a physical

stimulus is no longer present (to inhibit visual persistence). In line with these theories, Lovegrove and his colleagues (1985, 1986, 1987, 1988) demonstrated that dyslexics had different patterns of visual persistence, than did normal readers, as the spatial frequency of stimuli was increased. Dyslexics were also differentiated from normal readers in that they showed less of a decrease in visual persistence as a function of increased contrast in sine-wave gratings. Finally, dyslexics were found to differ from normal readers in contrast sensitivity as a function of spatial frequency, and as a function of temporal frequency; the dyslexic children had lower contrast sensitivity than normal readers throughout a range of spatial and temporal frequencies and the differences between the two groups increased as spatial or temporal frequency increased. Dyslexics appear to have a deficit in the inhibition of visual persistence and in the functioning of their flicker detection mechanisms. However, when the sustained system functioning of dyslexics and normal readers was investigated in terms of orientation bandwidth, spatial frequency bandwidth and the oblique effect, no differences between the groups were found.

Collateral support for low level visual processing dysfunction in dyslexics is found in an electrophysiological study conducted by Mecacci, Sechi and Levi (1983). Evoked potential amplitude recorded from left and right occipital

locations of dyslexics was compared to that of age-matched controls. The stimuli were checkerboard patterns of varying check sizes which were flashed on a computer monitor. The amplitude of the evoked response was found to be larger in the control subjects than in the dyslexics for all check sizes. Other research has indicated that processing of checkerboards of varying check size and processing of sine-wave gratings of varying spatial frequencies are mediated by common mechanisms. Therefore, these results were interpreted as supporting the findings of experiments which had investigated low level visual processing of dyslexics through the spatial frequency analysis paradigm.

Differences Between Dyslexics and Normal Readers in Higher Level Visual Processing Presumed to Be Associated with the Transient Visual System

Demonstration of low level visual processing deficits in dyslexics, relative to normal controls, does not demonstrate that these deficits play a role in the inadequate acquisition of reading skills in these children (Lovegrove et al., 1986). Experiments which investigate higher level visual perception skills which would be expected to be impaired in dyslexics relative to normal reader, if dyslexics have low level visual processing deficits, represent a step towards more directly connecting reading impairment with impairment in low level visual processing.

May, Williams and Dunlap (1988) used a modified method of constant limits to measure threshold for temporal order judgement in dyslexics and normal readers. The stimuli "BOX" and "FOX" were presented on a computer monitor for a brief duration, in vertical or horizontal display. Temporal order threshold was measured as the interstimulus interval (ISI) at which correct detection of which stimulus was presented first was made with 75% accuracy. The ISI at which the dyslexics achieved 75% accuracy was significantly longer than the ISI at which the normal readers did the same. May et al. (1988) thought that this increased threshold for perception of temporal order in dyslexics could be explained within the context of the dyslexics having longer duration of visual persistence than did the normal readers. It was reasoned that increased visual persistence could cause difficulty in distinguishing the off-set of the first stimulus from the on-set of the second stimulus, and therefore, the dyslexics required more time to accurately determine temporal order.

Brannan and Williams (1988) also investigated threshold for temporal order judgement in good and poor readers. Using the same method and procedure as May et al. (1988), Brannan and Williams (1988) replicated the results of May et al. (1988) and extended their findings to a wider age range of children and to non-word ([#] and [&]) visual stimuli. They found that, for all stimuli, dyslexics were 75%

accurate in determining which stimulus was presented first at a longer duration ISI than the normal readers. Since there was no significant difference in temporal order threshold for word and non-word stimuli, these results were combined and were found to be significantly correlated with reading level.

Brannan and Williams (1988) investigated the relationship between temporal order threshold and reading by conducting a post-hoc analysis of dyslexics and reading-level matched controls selected from normal readers. They found that, even when reading level was matched, the dyslexics had significantly higher threshold for temporal order than the normal readers.

Williams and Bologna (1985) investigated deficiency in the transient visual system of dyslexics by measuring the effect of perceptual grouping upon the length of time need to complete a card sort task. Perceptual grouping was defined as linking elements into figures and regions, such that elements that are similar to or physically close to one another will group into the same perceptual unit. They postulated that the time required to sort two-element stimuli, on the basis of only one of the elements, would be longer if the two elements were similar and lent themselves to perceptual grouping than if the two elements were dissimilar and did not lend themselves to perceptual grouping. Low-average (at least 1 year below grade level),

and high-average (at least 1 year above grade level) fourth-grade readers were compared on a speeded, card sort task. For all children, sorting time was longer when the elements of the two-element stimuli were similar than when they were dissimilar. The magnitude of the perceptual grouping effect was calculated as the difference in the length of time required to sort two-element stimuli which were similar, and the length of time required to sort two-element stimuli which were dissimilar. This grouping effect was found to increase as reading ability decreased. Further, the dyslexics had significantly larger grouping effects than normal readers.

Williams and Bologna (1985) reasoned that this perceptual grouping task required a type of holistic visual processing in which large amounts of general visual information would have to be rapidly processed. Their theorized holistic visual system resembles the previously discussed transient system in that it rapidly processes information in the peripheral visual field. It's counterpart, the analytic system, resembles the previously discussed sustained system in that it processes specific details about stimuli and relies upon foveal vision. The functions of the holistic system are thought to be to conduct a crude analysis of incoming stimuli, break the field into regions and units, and to direct the analytic system to focus attention on particularly salient areas.

Therefore, within this context, perceptual grouping could be a type of holistic processing. Consequently, Williams and Bologna (1985) postulated that dyslexics had a deficit in holistic or transient system functioning.

Brannan and Williams (1988) also replicated Williams and Bologna's (1985) results and extended them to a wider age range of dyslexics and normal readers. Using the same task and procedure as Brannan and Williams (1988), they also found that it took longer to sort two-element stimuli that lent themselves to perceptual grouping than it did to sort two-element stimuli that did not lend themselves to perceptual grouping. Further, eight-year-old dyslexic and normal readers did not differ significantly in the magnitude of this grouping effect. However, 10- and 12-year-old dyslexics had a significantly larger grouping effect than the 10- and 12-year-old normal readers. In addition, a significant negative correlation, which accounted for 42% of the variance in reading level, was found between reading level and the magnitude of the perceptual grouping effect.

Brannan and Williams (1988) further investigated the relationship between the perceptual grouping effect and reading by conducting a post hoc analysis of dyslexics and reading-level matched controls who were selected from the normal readers. They found that, even when reading level was matched, dyslexics had a significantly larger perceptual grouping effect than the normal readers.

Solman and May (1990) investigated the perceptual consequences of a transient system deficit in dyslexics by examining these children's ability to locate the position of letters and patterns. They theorized that, since the transient system preferentially responds to stimuli presented to the peripheral visual field, visual perception tasks presented to the peripheral visual field should be compromised in dyslexics. Further, they theorized that if the transient system is primarily responsible for rapid encoding of spatial location information, dyslexics should have greater difficulty locating the position of visual stimuli as they are presented further and further from the central visual field.

Solman and May (1990) selected the best and worst readers from a group of third graders, who had taken a standardized reading comprehension and word recognition test. A shape (a cross embedded in a circle) or an upper case letter, located in one cell of a square matrix, was briefly presented on a computer monitor. The location of the stimulus within the matrix was varied, ranging from central visual field to increasingly peripheral visual field. Following this, an empty matrix was displayed and the child had to point to the cell that had previously contained the stimulus. When the stimulus was an upper case letter, the child also had to name the letter.

Solman and May (1990) found that the poor readers were significantly less accurate than the good readers at naming letters. Both groups were less accurate in letter naming as the stimulus location became increasingly peripheral. The significant finding of this experiment was that poor readers were no less accurate in recalling spatial location than the good readers when stimuli were located near the central visual field. However, their accuracy decreased significantly more than the good readers as the stimuli were located increasingly in the peripheral visual field.

Solman and May (1990) then compared the same groups on their ability to locate two upper case letters or two shapes within a matrix. The location of the first stimulus was randomly selected from one of the locations employed in the previous experiment. Following a brief delay, the second stimulus was then located in one of the cells diagonally opposite the location of the first stimulus. The procedure was the same as in the previous experiment except that the child had to touch the screen with one finger of each hand. This experiment replicated the results of the previous experiment with the additional finding that, for both groups, the amount of error in locating stimuli was greater for the second target.

Current Research in Auditory Processing in Dyslexics

Auditory processing has been defined as the ability to effectively receive, attend to, decode, understand, store,

manipulate and apply auditory information (Katz & Wilde, 1985). This definition covers a wide range of cognitive functions (attention, memory, perception), as well as input and output of different auditory stimuli (tones, phonemes, syllables, words). There are different schemes for organizing the components and processes included in this definition. Wagner and Torgesen (1987) felt that auditory processing is an integration of three types of cognitive processing: phonological awareness, which is the awareness of and access to the sounds of one's language; phonological recoding in lexical access, which involves the phonetic decoding of printed words; and finally, phonetic recoding to maintain information in working memory, which allows the storage of sound-symbol associations in working memory as part of ongoing processing, such as blending sounds to form words.

On the other hand, Jerger, Martin and Jerger (1987) organized auditory processing into three hierarchical levels within the context of an information processing model. The first level involves the transformation of the sound wave into a neural signal. At the next level, phonetic-phonological analysis is conducted, and at the final level, linguistic functioning occurs as the basic units of the second level become associated with grammatical structure and/or semantic content. In the following review of research relating to auditory processing in dyslexic

children the scope of the term auditory processing will be limited to the first and second level of organization as described by Jerger et al. (1987). Thus, auditory processing will be defined as transformation of a sound wave into a neural signal and phonetic-phonological analysis of that neural signal.

Differences between Dyslexics and Normal Readers at the Level of the Transformation of the Sound Wave into a Neurally Encoded Signal

Studies assessing the integrity of basic auditory functions in dyslexic children have relied primarily upon the measurement of brain stem auditory evoked potentials (BAEP). BAEP is best understood within the context of the electroencephalogram (EEG) and evoked potentials (EP). The EEG is a record of spontaneous random fluctuations of electrical activity in the brain, which occur in the absence of specific sensory stimulation (Jacobson & Hyde, 1985; Martin, 1986). Dominant frequencies and amplitudes observed in the EEG record are Alpha waves (8-13 Hz), beta waves (13-30 Hz), delta waves (0.5-4 Hz) and theta waves (4-7) Hz (Martin, 1986). EP are bioelectrical events that are related to sensory stimulation (in the auditory system these are generally clicks, brief tone pips or tone bursts). They are not readily apparent from the EEG record but can be extracted through the use of special computerized averaging and summation programs (Jacobson & Hyde, 1985; Martin,

1986). The nomenclature for EP wave components generally involves the wave's polarity (positive or negative as recorded from the scalp) and its order in a sequence of waves or its latency in msec (Jacobson & Hyde, 1985). The components of auditory evoked potentials (AEP) may also be classified according to certain ranges in latency. Slow AEP have a latency of 50 to 200 msec (Jacobson & Hyde, 1985). Middle latency AEP are in the range of 15 to 50 msec (Jacobson & Hyde, 1985). Fast AEP responses or BAEP (thought to originate in the eighth cranial nerve and in the auditory pathways which ascend through the brain stem) have a latency in the range of 2 to 10 msec (Jacobson & Hyde, 1985). The BAEP is comprised of seven components: wave I represents cochlear nerve activity; wave II, cochlear nucleus activity; wave III, superior olive activity; waves IV and V, inferior colliculus activity; and waves VI and VII, thalamic activity. The latency and the amplitude of AEP and BAEP waves are measured (Martin, 1986). Pathology of the eighth nerve or the brain stem can be inferred by examining the BAEP record for abnormalities in wave morphology, and/or for delays between one or more of the waves (Josey, 1985).

Pinkerton, Watson and McClelland (1989) measured BAEP response in poor readers and normal controls. Even though wave morphology and latency were within normal limits for age for both groups, some differences were noted.

Specifically, the controls showed greater amplitude in waves III and V to right-ear stimulation as compared to left-ear stimulation. This right/left ear difference was absent in poor readers. In addition, the interval between waves I and V was significantly shorter to left-ear stimulation in the poor readers than it was in the normal readers. These findings were interpreted as indicating that the poor readers showed a loss of normal dominance in the right-ear sensory pathway and that this loss of dominance was related to greater efficiency in the left-ear sensory pathway rather than to deficiency in the right-ear pathway.

Jerger et al. (1987) measured BAEP in one dyslexic boy and three normal controls. The morphology of waves I, II and III of the experimental subject and the normal controls on the left ear were comparable. However, in the right ear, the corresponding peaks were degraded for the dyslexic boy as compared to the controls, suggesting that, in this particular dyslexic boy, acoustic stimuli may not have been transformed into an appropriate neural signal. Such deviations in the structure of waves I, II, and III could reflect abnormality at the level of the eighth nerve or brain stem auditory pathways (Josey, 1985).

While the results of these investigations suggest that the basic auditory processing of dyslexics is compromised, their overall findings were weak, and there appears to be minimal data to support such a conclusion.

Differences Between Dyslexics and Normal Readers at the Level of Phonemic-Phonological Analysis

The next level of auditory functioning, phonemic-phonological analysis, has also been investigated through the use of AEP and EEG. In addition, through manipulation of the parameters of auditory processing tasks, investigators have documented phonemic-phonological deficits, and delineated the nature of these deficits in dyslexic children.

Flynn and Deering (1989) recorded EEGs of school-identified dyslexic children, who had been classified according to Boder's classification system. Boder's (1973) system for classifying dyslexics is probably the most widely utilized and researched classification model to date. In this model, three distinct subtypes of dyslexia have been identified: dyseidetic, dysphonetic and alexic. They recorded EEG's for these subgrouped dyslexics under seven conditions: resting with eyes closed (baseline), silent reading at independent reading level, silent reading at frustration reading level, spelling dictated words, spelling recognition, blending sounds into words and indicating the approximate time on a clock face that had been drawn by the child. The EEG record during the six experimental conditions was compared to the resting/baseline EEG, and these differences were examined across groups. The only significant difference found between the groups was that

during frustration level reading, spelling recognition and clock drawing there was a significant increase in left temporal-parietal theta activity in the dyseidetic group while the other groups showed decreased theta activity. In a second study, which attempted to replicate these findings, significantly increased left temporal-parietal theta activity in the dyseidetic group was again noted but, this time it occurred during independent reading. Since increased theta power in the EEGs of the dyseidetic children was noted in mid-temporal and temporal-parietal regions, which overlie cortical areas presumed to be involved in phonetic decoding and sequencing of linguistic material (the angular gyrus), these authors postulated that dyseidetic children may be characterized by over-use of linguistic abilities rather than by deficient visual-spatial skills.

Pinkerton et al. (1989) conducted a power spectral analysis of the EEG records of poor readers and normal readers. They found power for delta, theta, alpha and beta activity, with eyes open and closed, was significantly elevated in the poor readers as compared to the normal readers. An additional difference was found between the groups in that delta band power was increased in the temporal regions as compared to the centro-parietal regions for the poor readers but not for the normal readers. They also analyzed the EEG records for AEP. The only significant difference found between the groups was that the temporo-

frontal P1 amplitude of the left hemisphere was significantly lower in the poor readers than in the normal readers. These combined findings were interpreted as indicating disturbed late auditory response in poor readers. It was postulated that these findings could reflect an impairment in processing auditory information or impaired ability to focus attention.

Attempts to delineate the nature of impaired auditory processing in dyslexic children were preceded by examination of auditory processing in children who were severely impaired in the acquisition of spoken language (developmental aphasia). As it is directly relevant to the investigation of auditory processing in dyslexic children, some of this literature will be briefly reviewed here.

Tallal and Piercy (1973) investigated the ability of developmental aphasics and controls to perform auditory discrimination tasks and to perceive and reproduce sequences of nonverbal stimuli. The auditory discrimination task required the subjects to make same/different judgements about pairs of tones. Perception and reproduction of sequence was assessed by using a test, called the Repetition Test, which was developed by the researchers. In the Repetition Test, subjects were first trained to press a particular panel after hearing a particular tone (Press panel 1 in response to hearing tone 1 and panel 2 for tone 2). Then the tones were presented in various sequences (1-

1, 2-1, 1-2, 2-2) and the subjects were required to reproduce the sequence by pressing the correct panels, in the correct order. On both the auditory discrimination test and the Repetition Test, the interstimulus interval (ISI) was manipulated; ISI was systematically increased to 4062 msec or decreased to 8 msec, relative to a baseline ISI of 428 msec which had been employed during training. The developmental aphasics were impaired on both tasks, relative to normal controls, only when the ISIs were brief. Tallal and Piercy (1974, 1975) went on to examine auditory discrimination, as well as perception and reproduction of temporal sequences of specific speech stimuli in developmental aphasics. They concluded that developmental aphasics had a specific auditory processing impairment for brief transitional auditory information (i.e. stop consonants).

Tallal (1980) extended the findings of Tallal and Piercy (1973) to reading-impaired children by assessing their performance on the same auditory discrimination test and the Repetition Test, relative to normal controls. In this study, ISI was only decreased systematically from a baseline of 428 msec to 8 msec. Similar to the developmental aphasics, the reading-impaired children showed impaired auditory discrimination, as well as impaired temporal pattern perception and reproduction, when non-verbal stimuli were presented rapidly; the reading-impaired

children made significantly more errors than the normal controls on both tasks as ISI decreased. These results were interpreted as suggesting that the rate of presentation of auditory stimuli influences auditory processing in reading-impaired children.

In an attempt to determine the relationship between auditory processing and reading, Tallal (1980) administered a reading achievement test and a test of phonetic decoding of nonsense words to the reading-impaired children. Correlation of the results of these tests with the results of the auditory discrimination and repetition tests showed that the number of errors in decoding nonsense words was positively and significantly correlated with number of errors on the Repetition Test. A significant positive correlation was also found between accuracy on the auditory discrimination task and scores on the spelling, word discrimination and word knowledge subtests of the reading achievement test. Based upon these data, Tallal hypothesized that difficulty in analyzing rapidly presented auditory information affected efficient analysis of phonetic code, and eventually caused impairment in reading.

Reed (1989), working with reading-disabled children, replicated and extended Tallal's (1980), as well as Tallal and Piercy's (1974, 1975) findings. She compared the performance of reading-disabled children on Tallal and Piercy's (1973) Repetition Test and two other discrimination

tasks to that of normal controls. Stimuli used in the Repetition Test included consonant-vowel (CV) syllables and steady-state vowel syllables, in addition to tones. Training was conducted using a 400 msec ISI, and during testing, the ISI was systematically decreased to 10 msec. The children were also tested for their ability to discriminate syllables along a nine point place-of-articulation continuum in which /ba/ and /da/ were endpoints. They were required to make same/different judgements for pairs of these nine stimuli; each of the nine stimuli were either paired with themselves or were paired with the syllable two steps away in either direction along the continuum. Finally, the children were tested in their ability to choose between pairs of pictures representing words which differed only in their initial stop consonant.

On the Repetition Test, shortened ISI had no effect on either group's ability to reproduce temporal patterns consisting of two vowels; however, the reading-disabled group made significantly more errors than the normal controls when Repetition Test stimuli were tones or CV syllables. The two groups also differed in their ability to discriminate between syllables along a continuum; the reading-disabled children made more errors discriminating between pairs of syllables which were in the middle of the continuum. Finally, the reading-disabled children made more errors than the controls on the picture-matching task.

These results replicated Tallal's (1980) finding of impairment in auditory processing of briefly presented non-verbal stimuli among reading-disabled children. These reading-disabled children also showed difficulty processing stop consonants when they were presented briefly, as did the developmental aphasics studied by Tallal and Piercy (1974, 1975). However, it was additionally demonstrated that the reading-disabled children had difficulty processing stop consonants when they occurred naturally within words.

All children performed well on the repetition task when steady-state vowel syllables were used as stimuli. To rule out the existence of a confound due to a ceiling effect, Reed tested the most severely disabled children in her index group and their matched controls on the same task with added white noise. In general, the addition of ipsilateral competing white noise makes tests more sensitive to auditory processing dysfunction as it reduces the redundancy of the syllables used in the test (Mueller, 1985). The addition of white noise did not differentially effect the performance of either group. The reading-disabled children continued to be able to accurately process steady-state vowel stimuli even when the stimuli were presented for brief intervals. This suggested that the reading-disabled children had a selective deficit in processing brief auditory cues (stop consonants), but not auditory cues that were available over a lengthy period of time (vowels), when both were rapidly presented.

A problem with Tallal's (1980) and Reed's (1989) findings is that a deficit in processing temporal auditory information is inferred from the reading-disabled children's impaired reproduction of sound sequences on the Repetition Test; auditory discrimination of temporal patterns was not directly assessed. Elliott, Scholl, Grant and Hammer (1990) investigated this potential confound.

Elliott et al. (1990) tested dyslexic children and normal controls on their ability to perform a fine-grained auditory discrimination task. This task measured perception of acoustic, not phonemic differences, by requiring the subjects to make same/different discriminations about two stimuli along continuum of synthesized consonant-vowel (CV) syllables which varied in voice-onset-time (ba-pa) and place-of-articulation (da-ga) by just-noticeable-differences. Manipulation of voice-onset-time was thought to assess temporal discrimination while manipulation of place-of-articulation was thought to assess frequency discrimination. The dyslexics were poorer in discriminating voice-onset-time but not place-of-articulation. This result was interpreted as indicating that dyslexic children have difficulty hearing small acoustic temporal differences.

The same dyslexic children and a different group of control subjects were also assessed on their ability to perform an auditory closure task. Auditory closure was assessed by using a forward gating paradigm in which only

initial portions of highly familiar monosyllable words were monaurally presented for word identification. The initial gate duration was 120 msec. This gate duration was extended by 60 msec each time the child failed to identify the word. The total gate duration at which the subjects correctly identified the word was measured. The average gate duration for correct identification of words did not differ between groups. This result was interpreted as indicating that the auditory closure skills of the dyslexic children were comparable to those of the control children.

Snowling, Goulandris, Bowlby and Howell (1986) assessed phoneme segmentation in dyslexics, age-matched (CA) controls and reading-ability-matched (RA) controls by having them repeat low frequency and high frequency one-syllable words, as well as nonsense syllables, under three levels of signal to noise ratio (no noise, low noise and high noise). Snowling et al. postulated that in order to repeat nonsense syllables subjects would have to rely on phonemic segmentation. While the repetition of known words would be facilitated by stored lexical-phonological representations, and repetition of low frequency words would probably involve both processes. Accordingly, they felt that repetition of nonsense syllables would be differentially affected by the introduction of noise masking. The introduction of noise should affect repetition of real words (low and high frequency) less than repetition of nonsense syllables

because subjects would be able to access an already existing articulation routine to compensate for noise masking. While the introduction of noise level did have the expected differential affect upon accuracy in repeating nonsense syllables, low frequency words and high frequency words, it did not differentially affect the performance of the three groups. Regardless of the noise level introduced, there was no difference between groups in their ability to repeat high frequency words; however, differences were noted between groups in their ability to repeat low frequency words and nonsense syllables. CA controls were significantly better than RA controls and dyslexics in repeating low frequency words. RA controls differed from dyslexics only in that they were significantly better at repeating nonsense syllables.

Snowling et al. (1986) hypothesized that RA controls and dyslexics performed less well than the CA controls in repeating low frequency words because of poor word knowledge. Consequently, when they were confronted with unknown low frequency words they had to rely upon phonemic segmentation while the CA controls recognized the low frequency word and were able to employ lexical-phonological representation. To test this hypothesis, the three groups were given an auditory lexical-decision task in which they had to decide between words and non-words under low noise and no noise conditions. Again, there was no differential

effect of noise between groups, and CA controls performed significantly better than the dyslexics and the RA controls. These combined results were interpreted as suggesting that dyslexics have a specific deficit in phoneme segmentation.

Differences Between Dyslexics and Normal Readers in Both
Auditory and Visual Processing

Fewer studies have investigated auditory and visual processing in the same group of disabled readers. Johnston, Anderson, Perrett and Holligan (1990) examined both visual and auditory segmentation in poor readers as compared to CA and RA controls. Using higher level cognitive tasks presumed to assess visual segmentation (Children's Embedded Figures Task) and auditory segmentation (identify odd word out from a set of three dictated words in which initial, medial or final phoneme was varied), they found that the poor readers performed significantly below CA controls but not significantly below RA controls on both tasks.

Hardy, McIntyre, Brown, and North (1989) found that, when auditory and visual processing were assessed with more discrete tests than those employed by Johnston et al. (1990), dyslexics were impaired relative to normal controls. Pairs of letters were simultaneously or sequentially presented on a tachistoscope to dyslexics and age-matched normal readers. The composition of the letter pairs was varied according to whether the letters were identical, visually confusable, aurally confusable, or neither visually

nor aurally confusable. The children were required to determine whether the letters in each pair were the same or different and to press a corresponding key. Reaction time was the dependent variable. It was expected that, consistent with the dual route theory of word recognition, visual processing would occur more rapidly than auditory processing. Therefore, the effect of visual confusable letter pairs upon reaction time would be noted for simultaneous presentations, while the effect of aurally confusable letter pairs would be noted for sequential presentations. Indeed, the normal readers had a significantly longer reaction time for the aurally confusable letter pairs than they did for both the visually confusable and the neither visually nor aurally confusable letter pairs, when the letters were presented sequentially. Their reaction times for each type of letter pair were not significantly different when the letters were simultaneously presented. This result was interpreted representing an expected interference effect of confusability. Specifically, that visual confusability decreases and auditory confusability increases when letters are presented sequentially rather simultaneously. However, this effect was not found for the dyslexics. Hardy et al. interpreted the lack of interference effect of confusability in the dyslexics as reflecting impairments in both auditory and visual processing.

Conclusions and Hypotheses

There has been extensive documentation that dyslexics have auditory processing deficits or visual processing deficits. However, these studies, by primarily examining only visual or only auditory processing in dyslexics, have fostered the conception of dyslexia as a unitary disorder; that dyslexia is caused by a deficit in auditory processing, or it is caused by a deficit in visual processing. Reading is a complex, multi-staged, task which involves several input, output and mediating processes, not just auditory and visual processing (Gallagher, 1989; Mattis, French & Rapin, 1975). To conceive of a reading disorder as being solely related to impaired auditory or impaired visual processing, therefore, appears simplistic. It seems more likely that an impairment in any one of the critical processes, or in a set of processes, involved in reading could result in dyslexia (Mattis, French & Rapin, 1975). Investigations of both auditory and visual processing in the same group of dyslexics would help determine if dyslexia is a heterogeneous disorder by allowing the determination of whether subtypes of dyslexia, based on demonstrated weakness in auditory and/or visual processing, exist. However, such investigations have been limited in number and their results have been equivocal.

Among those researchers who did investigate both auditory and visual processing in the same group of dyslexic

readers, the use of a test battery composed of parallel tests within each modality appears to be absent. The use of tests which are purported to measure a specific function, but in reality measure several cognitive functions, is an unnecessary confound (Johnston et al., 1990). It would be preferable to use a battery of tests in which the only difference between the tests would be in the modality of stimulus presentation.

Another problem associated with the investigations reviewed above is the manner in which they identified their research subjects. The criteria for classifying children as dyslexic are, by necessity, different depending upon whether the child is being identified by school administrators and teachers, or by researchers (Morrison & Siegel, 1991; Wong, 1986). School administrators and teachers want a functional definition which will efficiently define dyslexia and provide the information necessary for remediation. On the other hand, researchers want a definition which will produce samples which are homogeneous and can be easily identified and replicated by other researchers (Wong, 1986). In spite of their distinct needs, researchers have employed the definitional criteria of administrators and clinicians, and in doing so, have inherited all the problems associated with operationalizing this definition. The result has been a wide variety of index groups rather than a consistently identified homogeneous sample. It would seem to be more

appropriate for researchers to adopt a clearly delineated operational definition of dyslexia such as that outlined by Morrison and Siegel (1991). Specifically, Morrison and Siegel's (1991) criteria for dyslexia are as follows: average intelligence (IQ test score greater than or equal to 80), below average achievement on a test of single word decoding (WRAT-R reading subtest score less than or equal to 25th percentile).

Few of the investigations reviewed above examined the performance of dyslexics relative to both RA controls and CA controls, and therefore, are limited in their ability to address the causal question. If dyslexics are impaired relative to CA controls, this impairment could have caused the reading disorder. Alternately, the same result would be obtained if the development of auditory and visual processing is facilitated by the acquisition of reading skills. The addition of a RA control group would support the perceptual deficit hypothesis of dyslexia, if dyslexics were impaired relative to both the RA and CA controls, because it would rule-out the possibility the development of auditory and visual processing skills is dependent upon the development of reading skills.

The purpose of this study was to investigate whether research-identified dyslexics could be differentiated from chronologically-age-matched normal readers (CA controls) and reading-ability-matched normal readers (RA controls) on the

basis of specific auditory and visual processing abilities. A battery of parallel visual and auditory perception tests, and a test of single word reading and spelling was administered to a group of dyslexics, CA controls and RA controls. It was hypothesized that the dyslexics, as a group, would have impaired auditory and visual perceptual abilities relative to both the CA and RA controls.

In addition, four groups of dyslexics were derived based upon their performance on the auditory and visual perception tests: an auditory-processing-impaired group, a visual-processing-impaired group, a group that was impaired in both auditory and visual processing, and a group that had no impairment in either auditory or visual processing. Then, these four dyslexic groups were compared to determine whether they could be differentiated according to the nature of their spelling errors. Specifically, it was hypothesized that the auditory-processing-impaired group would make more errors spelling phonetically regular words than the visual-processing-impaired group, but not the mixed-impairment group, and that the visual-processing-impaired group would make more errors spelling phonetically irregular words than the auditory-perception-impaired group, but not the mixed-impairment group.

METHOD

Subjects

One hundred sixty-four subjects were recruited from private and public elementary schools. In order to examine the relationship of basic auditory and visual processing skills to word recognition in beginning reading all subjects were between 6 and 9 years of age. The following inclusionary and exclusionary criteria, which are consistent with Morrison and Siegel's (1991) operational definition of learning disabilities, were employed. Each child achieved a standard score of at least 85 on either the Raven's Colored Progressive Matrices (RCPM) (Raven, 1981) or the Peabody Picture Vocabulary Test-Revised (PPVT-R) (Dunn & Dunn, 1981). Subjects were excluded if they were not primarily English-speaking, or if they obtained a score 2 standard deviations or more above the norm for their age and sex on the Hyperactivity Factor of the Conners Parent or Teacher Questionnaire (CPQ and CTQ, respectively) (Goyette, Conners & Ulrich, 1978). In addition, when possible, auditory and visual acuity screening test results were obtained from school records. Subjects were excluded if they failed either screening.

Twenty-seven subjects did not meet the criterion for performance on the RCPM or the PPVT-R. Thirty-seven subjects were excluded because they obtained too high a rating on the hyperactivity factor of the CPQ or the CTQ.

Two children were excluded because they did not pass an auditory or visual acuity screening, and two subjects withdrew during the course of the experiment. Thus, 95 children participated in the full protocol.

Children, who met the above criteria and obtained a standard score less than or equal to 77 on the Reading subtest of the Wide Range Achievement Test-Revised (WRAT-R) (Jastak & Wilkinson, 1984) were placed in the dyslexic group. Children who met the above criteria, and obtained a standard score greater than or equal to 85 on the WRAT-R Reading subtest (Jastak & Wilkinson, 1984) were placed in one of the normal control groups depending upon their chronological age or absolute reading level. The reading-ability-matched control (RA control) group was equated for absolute reading level (WRAT-R Reading subtest raw score) with the dyslexic group. The chronological-age-matched (CA control) group was equated for chronological age with the dyslexic group.

Twenty-nine research-identified dyslexics, 49 CA controls and 17 RA controls participated in the study. Table 1 summarizes the characteristics of all three experimental groups. There were disproportionately more males in the dyslexic group ($N = 27$) than in either the CA control group ($N = 25$) or the RA control group ($N = 12$) (chi square = 14.77, $p = .0006$). By design, the three groups differed significantly in chronological age with the

dyslexics and the CA controls being older than the RA controls ($F = 25.37, p < .001$). Also by design, the groups differed significantly in absolute reading level with the CA controls reading at a higher grade level than both the dyslexics and the RA controls, who were not significantly different from each other ($F = 138.35, p < .001$). The groups were also significantly different in reading ability, as measured by standard scores, such that the CA controls performed significantly better than both the dyslexics and the RA controls, and the RA controls performed significantly better than the dyslexics ($F = 150.41, p < .001$). The groups did not significantly differ on estimated non-verbal skills ($p > .05$) as measured by the RCPM, on estimated verbal skills ($p > .10$) as measured by the PPVT-R, or on parent ratings of hyperactivity ($p > .10$). However, they were significantly different on teacher ratings of hyperactivity with the dyslexics being rated as significantly higher on the CTQ than the CA controls, while the RA controls were not significantly different from either group ($F = 9.93, p < .001$). Since all children had to meet the criterion of being no more than 2 standard deviations above the mean for their age and sex on the CTQ hyperactivity factor, this result appeared to be inconsequential; in order to be in the study, children could not to be hyperactive according to screening with the teacher behavior rating scale.

Standard Measures

Conners Teacher Questionnaire (CTQ)

The CTQ is a 28-item, global, teacher-rating scale used for the identification of children with hyperactive behavior. In this study it was used to eliminate hyperactive children from the sample.

Conners Parent Questionnaire (CPQ)

The CPQ is a 48-item version of the Conners Parent Symptom Questionnaire. It was also used to eliminate hyperactive children from the sample.

Peabody Picture Vocabulary Test-Revised (PPVT-R)

The PPVT-R is a test of receptive vocabulary which has a moderate correlation with verbal-type intelligence tests. It generates percentiles, standard scores, mental age equivalents and chronological age equivalents. It was used to estimate verbal cognitive abilities.

Raven's Coloured Progressive Matrices (RCPM)

The RCPM is a test of general ability that does not require language, nor the application of academic skills for success. It generates percentiles and standard scores, and was used to estimate non-verbal cognitive abilities.

Wide Range Achievement Test-Revised (WRAT-R), Reading

Subtest

The reading subtest of the WRAT-R is a well standardized and reliable measure of single word

recognition. It generates percentiles, standard scores, and grade equivalents. It was used to generate a cut-off score for classifying dyslexic and normal readers.

Boder Test of Reading-Spelling Patterns (BTRSP)

The Boder (1973) dyslexia classification model identifies three subtypes of dyslexia: Dysphonetic dyslexics, Dyseidetic dyslexics and Alexic dyslexics. Dysphonetic dyslexics are characterized as being impaired in the application of phonetic decoding strategies, letter-sound integration, and auditory memory. Dyseidetic dyslexics are described as having poor visual perception skills and weak visual memory. Boder's Alexic subtype is characterized as having impairments in visual perception and in using phonetic decoding strategies.

The BTRSP is a test of single-word reading and spelling, which is designed to assist clinicians in the systematic classification of children into one of these three dyslexic subtypes, or as a normal reader or a delayed reader (Boder & Jarrico, 1982). To assess spelling, children are dictated two types of words: words which they had accurately and rapidly decoded, and words which they were unable to decode or decoded very slowly. Consequently, the spelling test yields two scores, both of which were dependent variables in this study: percentage of known words spelled correctly, and percentage of good phonetic equivalents (percentage of unknown words spelled correctly,

plus unknown words spelled incorrectly but with good phonetic approximation). Test-retest reliability, over a period of two months, was .76 for percentage of known words spelled correctly, and .89 for percentage of good phonetic equivalents. Due to the subjective nature of scoring good phonetic equivalents, two raters whose inter-rater reliability was .90, were used to obtain the percentage of good phonetic equivalents in this study.

The majority of clinical and electrophysiological research on the Boder classification system, and the BTRSP provides evidence for concurrent validity (Flynn & Boder, in press). Electrophysiological investigations have discriminated between Dysphonetics and Dyseidetics on the basis of EEG or evoked potential patterns (Fried, Tanguay, Boder, Doubleday & Greensite, 1981; Flynn & Deering, 1989). However, neuropsychological investigations have yielded conflicting results. While analysis of WISC-R subtests, according to Bannatyne's spatial and sequential factors, indicated that significantly fewer Dysphonetics than Dyseidetics or Alexics showed spatial composite scores that were 1 standard deviation below their sequential composite score (Telztow, Century, Redmond, Whitaker & Zimmerman, 1983), analysis of sequential and simultaneous processing scores on the Kaufman Assessment Battery for Children (KABC) failed to distinguish between Dysphonetics and Dyseidetics (Hooper & Hynd, 1985; Kempa, Humphries & Kershner, 1988).

Hooper and Hynd (1985) suggested that more sophisticated neurolinguistic evaluation procedures than the KABC and the WISC-R might be needed to distinguish between the subtypes. Indeed, when compared on a more discrete measure of auditory processing, the Lindamood Auditory Conceptualization Test (Lindamood & Lindamood, 1971), Dysphonetics were differentiated from normal readers, and from dyslexics who produced good phonetic equivalents when spelling unknown words (Nockleby & Galbraith, 1984).

Experimental Measures

Visual and auditory perception of temporal order, discrimination, and closure were measured using the following tests. Each test was run on a Toshiba T-1200 laptop computer by a program written in QuickBasic.

The Visual Discrimination Test (V-DISCRIM)

Pairs of visual stimuli (##, #&, &#, &&) were sequentially presented, in the V-DISCRIM. Each stimulus in the pair was presented for a duration of 85 msec and a variable ISI was interposed between the two stimuli. The pairs were presented in horizontal display with each stimulus in the pair located at approximately one degree of visual angle subtended from the child's eye, to the right or left of the center of the computer monitor. Whether the stimuli were presented in a right-then-left or left-then-right sequence was randomly determined. The child was required to make same/different discriminations for each

pair of visual stimuli and to press the designated key on the computer keyboard. A total of 108 experimental trials were presented in three blocks. Each block was composed of four trials (one for each possible pairing of stimuli) at each of nine ISIs (40, 55, 70, 85, 100, 115, 130, 145, 160 msec). Trial order was randomized for each block.

The child was given four demonstration trials and eight practice-with-correction trials using a 160 msec ISI. Experimental trials were initiated after the child achieved at least 80% accuracy on twelve practice-without-correction trials, which also used a 160 msec ISI. The test was discontinued if the child did not achieve the criterion within three presentations of the practice-without-correction blocks.

To minimize the sustained-attention and memory components of the task, trials were initiated 1 sec. after the child made his/her response, and short delays were interposed between blocks of trials with the initiation of the next block of trials being under the control of the child. Also, 1 sec prior to the presentation of the first stimulus in each pair, an "X", which was accompanied by a beep, was presented for a duration of 1 sec. in the center of the monitor to alert the child to the initiation of the next experimental trial and to focus visual attention to the center of the monitor.

The Auditory Discrimination Test (A-DISCRIM)

The A-DISCRIM was a modification of Tallal and Piercy's (1974) discrimination task. Pairs of auditory stimuli (300 Hz tone/300 Hz tone, 300 Hz tone/915 Hz tone, 915 Hz tone/300 Hz tone, 915 Hz tone/915 Hz tone) were sequentially presented through headphones. Each tone was presented for a duration of 15 msec. A variable interstimulus interval (ISI) was interposed between the two stimuli. The child was required to make same/different discriminations and to press the designated key on the computer keyboard. A total of 96 experimental trials were presented in four blocks of 24 trials each. Each block was composed of four trials (one for each possible pairing of stimuli) at each of six ISIs (4, 8, 15, 30, 60, 150 msec). Trial order was randomized for each block.

Each child was given four demonstration trials and eight practice-with-correction trials using a 305 msec ISI. Experimental trials were initiated after the child achieved at least 80% accuracy on twelve practice-without-correction trials, which also used a 305 msec ISI. The test was discontinued if the child did not achieve the criterion within three presentations of the practice-without-correction blocks.

Again, to minimize the sustained attention and memory components of the task, trials were initiated 1 sec. after

the child made his/her response and short delays were interposed between blocks of trials with the initiation of the next block of trials being under the control of the child.

The Visual Temporal Order Test (V-TEMP)

The V-TEMP was a modification of a task employed by May et al. (1988) and Brannan and Williams (1988). The V-TEMP differs from the V-DISCRIM only in the following manner. The stimuli "#" and "&" were sequentially presented, in horizontal display, with a variable ISI interposed between the first and second stimulus. The child was required to determine whether the first stimulus was presented on the right or the left side of the monitor, and to press the designated key on the computer keyboard. The two stimuli remained visible until the child made his/her response. The four trials at each ISI per block were composed of each stimulus presented first while located on the right, and the left side of the monitor.

The Auditory Temporal Order Test (A-TEMP)

The A-TEMP was a modification of Tallal and Piercy's (1974) Repetition Test. The A-TEMP differed from the A-DISCRIM only in the following manner. A 300 Hz and a 915 Hz tone were sequentially presented for 25 msec, through headphones, with a variable ISI interposed between the two tones. The child was required to press the key corresponding to the particular tone that was presented

first. The two possible stimulus sequences (300 HZ/915 HZ or 915 HZ/300 HZ) were each presented twice, resulting in four trials for each ISI, per block.

Prior to the presentation of demonstration, practice-with-correction and practice-without-correction trials, the child was trained to press a particular key in response to the 300 Hz tone, and to press another key in response to the 915 Hz tone. This training was conducted for isolated tones, as well as for simple discrimination of the two tones (either the 300 Hz or the 915 Hz tone was presented, and the child was required to press the designated key).

The Visual Closure Test (V-CLOSE)

The V-CLOSE was a modification of a task employed by DiLollo et al. (1983). The stimulus was a vertical line which was presented under two conditions. In the first condition, the vertical line was constructed in two parts with a variable ISI interposed between the presentation of the top half of the vertical line, and the presentation of the entire vertical line. In the second condition, the entire line was presented. The child was required to determine whether or not there was a break in the presentation and to press the corresponding key on the computer keyboard. The same ISIs employed in the V-DISCRIM and the V-TEMP were used in the V-CLOSE. A block was composed of two trials of each stimulus presentation condition (break or no break) at each ISI. As in the V-

TEMP, the vertical line remained visible until the child made his/her response. The V-CLOSE did not differ from the V-TEMP or the V-DISCRIM in any other manner.

The Auditory Closure Test (A-CLOSE)

A 300 HZ tone or a 915 HZ tone were presented under two conditions. In the first condition, a variable ISI was interposed between two 15 msec presentations of the same tone. In the second condition, the tone was presented once for 15 msec. The child was required to determine whether or not there was a break in the presentation, and to press the corresponding key on the computer keyboard. A block was composed of each stimulus presented once, under both stimulus presentation conditions (break or no break), at each ISI. The A-CLOSE did not differ from the A-DISCRIM in any other manner.

Procedure

After parental consent, and a completed CTQ and CPQ were obtained for a child, the RCPM, PPVT-R, WRAT-R, and BTRSP were administered. Test administration was in a fixed order (RCPM, PPVT-R, WRAT-R, BTRSP) believed to facilitate the development of rapport between the experimenter and the child and to maintain the child's motivation to perform. Following administration of the standardized measures, the first two experimental measures were also administered. If the child met the subject criteria, the remaining experimental measures were administered during a second

session. The entire protocol was completed in two approximately one-hour sessions.

The experimental measures were administered in pairs: A-TEMP and V-TEMP, A-DISCRIM and V-DISCRIM, A-CLOSE and V-CLOSE. The order of the pairs (TEMP, DISCRIM, CLOSE), and whether the first test in each pair was visual or auditory were counterbalanced separately across CA and RA subjects, as a group, and across dyslexic controls.

Data Analysis

For each of the experimental measures, the total number of correct responses was calculated. A chance score (i.e., 50% of the trials correct) was substituted when an experimental measure was not administered because a child did not achieve the criterion of 80% correct during the training trials. Thus, the total correct score for an auditory battery test that was not administered was 48 (50% of 96 total test trials), and the total correct score for a visual battery test that was not administered was 54 (50% of 108 total test trials). All scores were then converted to z-scores based on the entire sample.

Table 2 shows the correlation between age and the z-scores for each experimental measure, their two-tailed probabilities, and the extent to which the variance in z-scores was accounted for by age (r^2). Even though all of the experimental measures were significantly correlated with age, the variance associated with age was not statistically

controlled prior to conducting statistical analyses because, the dyslexic and RA control groups would no longer be equated for absolute reading ability if the variance associated with age was also removed from the scores obtained on the measure upon which the two groups were equated (WRAT-R Reading raw score). Specifically, results of a one-way analysis of variance (ANOVA) examining WRAT-R Reading raw scores, after the variance associated with age was statistically controlled, showed that the groups were still significantly different from each other ($F = 127.93$, $p < .0001$). However, post-hoc testing indicated that while the CA controls continued to have a significantly higher reading level than both the dyslexics and the RA controls, the RA controls now had a significantly higher reading level than the dyslexics. Thus, when the variance associated with age was statistically controlled, the dyslexics and the RA controls were no longer equated for absolute reading level.

Primary Hypothesis Testing

To investigate whether dyslexics could be discriminated from CA Controls and RA controls on the basis of their performance on the experimental measures, a three-way mixed ANOVA was conducted with one between subjects factor and two within subjects factors. The between subjects factor was Group (Dyslexics, CA controls and RA controls). Modality of presentation (Auditory vs. Visual), and type of cognitive processing required to perform the test (Closure,

Discrimination or Temporal Order) served as within subject factors. When significant results were obtained, post-hoc testing was conducted using one-way ANOVAs, and the Tukey-Honestly Significant Difference (Tukey-HSD) procedure.

Next, discriminant function analysis was employed to determine if individual subjects could be correctly classified on the basis of their performance on the experimental measures. Stepwise variable selection was employed using the Mahalanobis distance method to safeguard against the possibility that the data might not represent a multivariate normal distribution. Due to the unequal sizes of the groups, it was specified that the classification variable categories be the same proportions as the actual groups being discriminated.

Secondary Hypothesis Testing

To more closely examine the characteristics of the dyslexic readers several post-hoc analyses were conducted. Due to the limited power of these analyses and to the increased probability of alpha error related to running these additional analyses, any significant findings need to be replicated.

The dyslexic group was divided into four groups: an auditory-processing-impaired group (N = 7), a visual-processing-impaired group (N = 5), an auditory-and-visual-processing-impaired group (N = 13), and a group that had no impairment in either visual or auditory processing (N = 4).

Impairment in auditory processing or visual processing was defined as an average standard score for the three auditory or the three visual processing tests, respectively, which was below zero. The derived groups were then compared on the two dependent measures obtained from the BTRSP (percentage of known words spelled correctly and percentage of good phonetic equivalents) using between groups, one-way ANOVAs. Again, when significant results were obtained, post-hoc comparisons were made using the Tukey-HSD procedure.

RESULTS

Primary Hypothesis Testing

To determine whether or not the dyslexics ($N = 29$) exhibited deficits in auditory or visual processing relative to both CA ($N = 49$) and RA ($N = 17$) controls, the data were analyzed using a mixed three-way ANOVA. A significant main effect was found for Group ($F = 8.16$, $p = .001$). However, no significant main effect ($p > .10$) was found for Modality (Auditory vs. Visual) or Process (Closure vs. Discrimination vs. Temporal Order). While the Group x Modality and Modality x Process interactions were not significant ($p > .10$), a significant Group x Process interaction ($F = 3.97$, $p = .004$) was obtained. The three-way interaction was not significant ($p > .10$). Post-hoc testing, designed to clarify the nature of the Group x Process interaction, indicated that, on both the closure and discrimination tests, the CA controls performed significantly better than the RA controls, while there was no significant difference between the dyslexics and either the CA or RA controls. However, on the temporal order tests, the CA controls performed significantly better than both the RA controls and the dyslexics, who were not significantly different from each other. The Group x Process interaction is represented in Figure 3.

To determine whether performance on the experimental measures could accurately predict group membership,

discriminant function analysis was conducted between pairs of groups. For each of these pairs, Table 3 shows the following information. First, the predictor variables are listed in descending order based upon the amount of information the variable added toward discriminating between the groups (as represented by Wilk's Lambda) with the level of significance for each variable. Finally, the table shows the percentage of members in each group for whom membership was correctly predicted and the overall percentage of subjects who were correctly classified.

The temporal order tests were consistently part of the functions obtained for discriminating between members of either group of normal readers (CA controls or RA controls) and members of the dyslexic group. The visual discrimination and the auditory closure tests were useful in discriminating between members of the two groups of normal readers. Overall, these results suggest that the visual discrimination and the auditory closure tests are useful for discriminating younger children from older children, or beginning readers from advanced readers, while the temporal order tests discriminate normal readers from impaired readers.

Post-Hoc Testing

As there was a disproportionate number of boys in the dyslexic group, compared to the CA and RA control groups (Chi Square = 14.77, $p = .0006$), the mixed three-way ANOVA

described above was repeated using only males in the dyslexic ($N = 27$), the CA control ($N = 25$), and the RA control groups ($N = 12$). The overall results of this analysis were the same as when the data for both males and females were analyzed. There was again only a significant main effect for Group ($F = 6.97$, $p = .002$) and a significant Group x Process interaction ($F = 2.98$, $p = .02$). However, this time post-hoc testing indicated that the CA controls performed significantly better than the RA controls only on the discrimination tests, rather than on both the discrimination and the closure tests, while the dyslexics's performance was still not significantly different from either the CA or RA controls. Further, on the temporal order tests, the CA controls performed significantly better than only the dyslexics, while the performance on the RA controls was not significantly different from either the dyslexics or the CA controls. This Group x Process interaction is represented in Figure 4.

To further explore the nature of the group-by-process interaction obtained during primary hypothesis testing (While the CA controls performed significantly better than the RA controls on all three types of cognitive processing tests, they performed significantly better than the dyslexics only on the temporal order tests), an additional three-way mixed ANOVA was conducted. This additional analysis was aimed at determining if the dyslexic's impaired

performance was related to differences in speed of processing temporal order information rather than, or in addition to, deficit in processing temporal order information. Group (dyslexics vs. CA controls vs. RA controls) again served as a between subjects factor, while Process (Closure vs. Discrimination vs. Temporal Order) and Speed (experimental trials with short ISI's vs. experimental trials with long ISI's) served as within subject factors. The ISI's were divided at the median ISI for each test. Thus, for the auditory and visual tests respectively, the shortest three or four ISI's were grouped together, and the longest three or four ISIs were grouped together. For each experimental measure, the total number of correct responses were computed for short and long ISI's. When significant results were obtained, post-hoc testing was conducted using one-way ANOVAs and the Tukey-HSD procedure, or paired t-tests.

A significant main effect was again found for Group ($F = 8.66, p < .001$). In addition, significant main effects were found for Speed ($F = 445.17, p < .001$), and Process ($F = 184.97, p < .001$). While significant two-way interactions were obtained for Group x Speed ($F = 4.22, p = .02$), Group x Process ($F = 4.55, p = .002$), and Process x Speed ($F = 23.15, p < .001$), the three-way interaction (Group x Process x Speed) was not significant ($p > .10$). The interpretation of the Group x Process interaction is described above in the

Primary Hypothesis Testing section. Post-hoc testing, designed to clarify the nature of the Process x Speed interaction, indicated that performance on all experimental measures improved (total correct responses increased) when experimental trials employed long ISI's rather than short ISI's. However, performance on the Closure tests was differentially affected by the use of long ISI's; performance on the Closure tests was more improved when long ISI's were used than was performance on the Discrimination and Temporal Order tests.

Post-hoc testing, designed to clarify the nature of the Group x Speed interaction, indicated that when short ISI's were used, the CA controls performed significantly better than the RA controls, while the dyslexics were not significantly different from either group. However, when long ISI's were used, the CA controls performed significantly better than both the dyslexics and the RA controls. This Group x Speed interaction is represented in Figure 5.

Secondary Hypothesis Testing

To determine whether dyslexics could be subgrouped according to impairment in auditory and/or visual processing, four derived groups of dyslexics were compared for accuracy in spelling words which they could rapidly and accurately decode, and words which they could not read or did not rapidly decode. Results of the one-way ANOVAs

indicated that auditory-processing-impaired, visual-processing-impaired, auditory-and-visual-processing-impaired and no-impairment groups did not significantly differ ($p > .05$) from each other in their ability to spell words which they could fluently and accurately decode, nor in their ability to correctly spell, or spell with good phonetic approximation words they couldn't decode or decoded slowly.

Since the results of the three-way mixed ANOVA suggested that dyslexics could be discriminated from normal readers based upon their performance on the temporal order tests, the dyslexics were also subgrouped according to their performance on these measures. Again four groups were derived: impairment in auditory temporal order processing only ($N = 8$), impairment in visual temporal order processing only ($N = 3$), impairment in auditory and visual temporal order processing ($N = 16$), and no impairment in temporal order processing ($N = 2$). Impairment was defined as a standard score below zero on either the auditory temporal order test or the visual temporal order test. These derived groups were also compared on the two dependent measures obtained from the BTRSP using between groups, one-way ANOVAs, and when significant results were obtained, post-hoc comparisons were made using the Tukey-HSD procedure. In contrast to the lack of significant difference between subgroups of dyslexics derived on the basis of auditory and/or visual processing deficits, dyslexics grouped

according to impairment in visual temporal order processing and/or impairment in auditory temporal order processing were significantly different in their ability to spell words they could not decode or that they had difficulty decoding ($F = 4.98, p = .008$). Post-hoc testing indicated that the dyslexics who had no impairment in both auditory and visual temporal order processing had a higher percentage of good phonetic equivalents than did dyslexics who had impairment in both auditory and visual temporal order processing. Dyslexics with impairment in either auditory or visual temporal order processing were not significantly different from either of these groups. These results are represented in Figure 6. It appears that dyslexics who had difficulty processing temporal order information, presented both aurally and visually, had a specific impairment in using phonetic rules to spell unknown words relative to dyslexics who had no impairment in processing temporal order information.

Additional Post-Hoc Testing

The dyslexic group was rated by teachers as being significantly more hyperactive than the CA or RA control group ($F = 9.93, p < .001$). To determine if the performance of the dyslexic group was related to teacher ratings of hyperactivity, correlations between the experimental measures and the Hyperactivity Factor of the Conners Teachers Questionnaire were computed, using a .01 level of

significance to control for the increase in alpha error associated with conducting multiple tests. Results of these analyses indicated that, for the dyslexics, performance on the experimental measures was not significantly related to teacher ratings of hyperactivity.

To get a better sense of the measures as tests of auditory and visual processing and/or as tests of specific types of cognitive processing (closure, discrimination and temporal order) a post-hoc factor analysis was also conducted. However, to appropriately assess the construct validity of these measures, these analyses would need to be conducted for a new sample of children. Principal components analysis was employed to extract factors, and an extraction criterion of eigen values greater than or equal to one was used. Determination of independent factors was made using varimax rotation. Only those variables that had final factor loadings above .50 were considered in interpretation of the resulting rotated factor matrix. The data were analyzed with the missing scores replaced by chance scores, as described above. However, a disproportionate number of dyslexics (52%) and RA controls (65%) than CA controls (27%) were not administered at least one of the experimental measures ($\chi^2 = 6.93$, $p = .05$). Since the children in the sample with the lowest absolute reading level had the most difficulty meeting the training criteria for the tests, it was felt that the

results of a factor analysis in which chance scores were substituted for missing scores might be confounded with the effect of reading level upon performance. Consequently, even though the size of the sample would be reduced to 56 from 95, a principal components factor analysis of the same methods and criteria as described above was also conducted without substituting chance scores for missing scores. In this case, listwise deletion of missing scores was employed.

When chance scores were substituted for missing scores ($N = 95$), a one-factor solution resulted which accounted for 45 percent of the variance in scores. However, factor analysis with no substitution of missing scores with chance values ($N = 56$), resulted in a two-factor solution which accounted for 57 percent of the variance in scores. Table 4 shows the rotated factor matrix obtained when missing values were not replaced. The visual closure test loaded on both factors, with a somewhat stronger loading on Factor 1. The other 5 measures more clearly loaded on a single factor. The auditory closure, auditory discrimination and auditory temporal order tests loaded on Factor 1, and the visual discrimination and visual temporal order tests loaded on Factor 2. Factor 1 was interpreted as representing an auditory processing factor while Factor 2 was interpreted as representing a visual processing factor. Thus, as originally proposed, most of the tests appear to be

differentially assessing auditory or visual processing.

DISCUSSION

The primary purpose of this study was to investigate the perceptual deficit hypothesis of dyslexia using a battery comprised of both auditory and visual perception tests, which differed in as few dimensions as possible. In order to more fully investigate the causal relationship between perceptual impairment and dyslexia, dyslexics were compared to reading-ability-matched normal readers, as well as to chronological-age-matched normal readers. Secondly, whether or not subgroups of dyslexics, derived on the basis of cognitive processing deficits, could be distinguished by differences in their acquisition of spelling skills was investigated.

Primary Hypothesis

Overall, the results from this study did not support the perceptual deficit hypothesis of dyslexia. Dyslexics were not differentiated from normal readers their same age, nor from younger normal readers who were reading at their same grade level, on the basis of deficits in auditory and/or visual processing. Rather, the data suggest that dyslexics are characterized by a specific deficit in processing temporal order information irrespective of the modality of presentation.

Specifically, the dyslexics performed significantly below the age-matched normal readers on the temporal order tests, but not on the closure and discrimination tests.

However, the dyslexic group's performance was not significantly different from that of the younger normal readers who were reading at the same grade level, on any of the tests. These younger normal readers performed significantly below the age-matched normal readers on the entire battery.

These results suggest that performance on the closure and discrimination tests is highly affected by age such that only younger normal readers performed less well than older normal readers. In contrast, reading achievement appears to make a contribution to temporal order processing because both younger normal readers and dyslexic readers performed significantly below older normal readers on the temporal order tests. These results also suggest that dyslexics have a specific deficit in temporal order processing as dyslexics performed significantly below normal readers their same age only in determining temporal order of rapidly presented sequences of non-verbal stimuli. However, because dyslexics were not impaired relative to both groups of normal readers, these results do not aid in determining whether the dyslexics's deficit in temporal order processing is causally related to their impaired acquisition of reading skills. The interpretation of these results in relation to the question of causality will be discussed in more detail below.

Lack of a significant Group (dyslexics vs. CA controls

vs. RA controls) x Process (Closure vs. Discrimination vs. Temporal Order) x Speed (short ISI's vs. long ISI's) interaction suggests that the dyslexic's deficit in temporal order processing is related to impairment in the cognitive processing skill itself, rather than to slow speed of processing on this particular cognitive task.

Interestingly, the significant two-way Group x Speed interaction suggested that dyslexic readers do not take advantage of the increase in processing time inherent in the use of longer interstimulus intervals. In addition, analysis of the performance of only males in each group did not suggest a gender effect (that the results of the study were affected by there being a disproportionate number of males in the dyslexic group as compared to the same-age normal reader group and the younger normal reader group). When the performance of only males in each group was analyzed, the dyslexics were again found to perform significantly below the normal readers their same age on only the temporal order tests.

The results of the discriminant function analysis provided additional evidence for the role of processing temporal order information in dyslexia. The temporal order tests were consistently part of the functions obtained for discriminating dyslexics from normal readers.

Overall, the results of this study were partially consistent with the findings of other investigations which

examined temporal order processing in only the auditory or only the visual modalities. Specifically, Tallal (1980) found that dyslexics had a deficit in processing rapidly presented sequences of non-verbal stimuli presented in the auditory modality, and May et al. (1988), and Brannan and Williams (1988) found that dyslexics were impaired in processing temporal order information for verbal and non-verbal stimuli presented in the visual modality. Similar to those studies, results of this investigation indicated that dyslexic children have a deficit in processing temporal order information. However, unlike Tallal's, May et al.'s and Brannan and Williams's findings, this deficit was not specific to the auditory or visual modality. Comparison of the results of this study with the findings cited above raises the question of whether the dyslexics's impairment in processing temporal order information is modality-specific, or is across all modalities.

When speed of processing is analyzed, the results of this study do not support the findings of Tallal (1980), May et al. (1988), and Brannan and Williams (1988). Specifically, Tallal found that dyslexics made significantly more errors on an auditory temporal order processing task as the duration of the interstimulus intervals was shortened. May et al., and Brannan and Williams found that dyslexics were 75% accurate in determining temporal order of verbal and non-verbal visual stimuli at significantly longer

interstimulus intervals than were normal controls. In this study, the dyslexics were significantly less accurate than normal readers their same age when interstimulus intervals were long, but not when interstimulus intervals were short, regardless of the type of cognitive processing required (closure vs. discrimination vs. temporal order). In contrast to the findings of Tallal, May et al., and Brannan and Williams, dyslexics did not show improved performance as a function of increasing the duration of interstimulus intervals. These results suggest that decreasing the speed-of-cognitive-processing demands was more beneficial to the overall performance of the normal readers than it was to the overall performance of the dyslexics.

Also, these results do not appear to support the findings of Lovegrove and his colleagues (1985, 1986, 1987, 1988). They theorized that dyslexics have a deficit in visual system functions, specifically transient visual system functions. To review, the transient visual system responds most strongly to short-duration, high-temporal-frequency stimuli which are presented to the peripheral visual field. The experimental tasks used to assess visual processing in this study were designed to assess these characteristics of the transient visual system. Short-duration stimuli were presented sequentially with successively shorter intervals interposed between the stimuli (increasing temporal frequency). In addition, for

the visual temporal order test and the visual discrimination test, the stimuli were presumed to be presented to the peripheral visual field. However, the dyslexics were not impaired on all of the visual processing tests. Further, while dyslexics were found to have a deficit in determining temporal order for rapidly presented sequences of non-verbal stimuli, this deficit was found for both the auditory and visual modalities, not just for the visual modality as the work of Lovegrove and his colleagues suggests.

It must be considered that these findings could be related to short term memory deficits in the dyslexic readers rather than to deficits in processing temporal order information. However, this appears to be unlikely. On all tests, the sequences to be recalled were very short, only two shapes or two tones. Thus, the overall memory load was low. However, the memory load on the temporal order tests was even less than that of the other tests in the battery because the children could respond as soon as the first stimulus was presented. In contrast, on the closure and discrimination tests both stimuli had to be presented before the child had the necessary information to make a correct judgement. The dyslexics were not significantly different from normal readers their same age on the closure and discrimination tests. However, they were discriminated from CA controls on the temporal order tests. Therefore, it seems unlikely that the performance deficit noted in the

dyslexics was related to an impairment in short term memory.

Question of Causality

A control group of normal readers who were reading at the same absolute level as the dyslexics, and were consequently younger than the dyslexics, in addition to a control group of age-matched normal readers, was employed to aid in determining whether cognitive processing deficits exhibited by dyslexics were causally related to dyslexia. It was reasoned that if dyslexics were impaired relative to both groups of normal readers this would strongly suggest that the deficit caused the reading impairment. Since dyslexics were impaired in temporal order processing relative to only the age-matched normal readers, rather than both the reading-ability-matched and the age-matched normal readers, impairment in processing temporal order information cannot be definitively established as a cause of dyslexia. However, it still can not be ruled out.

To restate the findings of this study, on temporal order processing tasks dyslexics performed significantly below normal readers their same age, but were not significantly different from younger normal readers who were reading at their same absolute level, regardless of the modality of presentation (auditory vs. visual). This result could be interpreted in one of three ways with each interpretation having different implications. The first interpretation is that the dyslexic group's deficit in

temporal order processing reflects a developmental delay. This implies that with advanced development, dyslexics will catch-up to age-matched normal readers and will eventually perform temporal order processing tasks with similar levels of accuracy. The second interpretation is that the development of this cognitive skill is facilitated by the acquisition of reading skills, that temporal order processing skills will improve as achievement in reading increases. The third interpretation is that the dyslexic's deficit in temporal order processing is causally related to dyslexia. If the temporal order processing skills of dyslexics improve at a significantly slower rate than do those of younger normal readers who were matched for reading level, and/or they never achieve the level of functioning exhibited by normal readers their same age, it would be reasonable to assume that the deficit in temporal order processing was causally related to dyslexia. Whether deficient temporal order processing skills are causally related to dyslexia, or are related to a developmental delay in the acquisition of these processing skills could be examined through a longitudinal or cross-sectional longitudinal study using these same experimental tasks. A treatment study in which temporal order processing skills were assessed prior to and following actual increase in reading achievement through remedial reading instruction would help determine if the acquisition of temporal order

processing skills is facilitated by the acquisition of reading skills.

Even if dyslexics had been shown to have a deficit processing temporal order information relative to both older and younger normal readers, questions about the relationship between low level cognitive processing skills and reading, would hinder the establishment of a causal relationship between impaired processing of rapidly presented sequences of auditory and visual stimuli and dyslexia.

Some investigators have argued that the question of causality cannot be addressed using laboratory tasks, such as the ones employed in this study, because they have a low ecological validity with reading (Hulme, 1988). It is felt that perception of stimuli such as sine-wave gratings are not comparable to the type of perceptual processing required for the acquisition of reading skills (Hulme, 1988). Alternately, it has been argued that tasks that test a theoretical model and do not involve reading are better for assessing the underlying cognitive problems related to dyslexia because their results are less likely to be confounded by the correlation between reading and the experimental tasks (Lovegrove, 1991).

While the processing of discrete, non-verbal stimuli, such as those employed in this study, is different from the visual and auditory processing required for reading, these stimuli have advantages over verbal stimuli such as letters

or words. The results obtained when non-verbal stimuli are used may be more easily and clearly interpreted. If letters or words were used as stimuli, the interpretation of these results would have to be qualified. The possibility that impaired performance was related to some verbal skill deficit, either solely or in addition to a deficit in processing rapidly presented temporal information, would have to be considered. Further, it would be impossible to attribute any obtained experimental effect to either one of these sources with a good degree of confidence.

This conflict could be addressed through a methodical and systematic study of temporal order processing in which hierarchies of stimuli ranging from low level processing (i.e., individual non-verbal stimuli) to higher level processing (i.e., letters or words) would be employed. The paradigm for the experimental tasks would remain the same, but successions of stimuli which have greater ecological validity with reading would be employed. Then, by comparing and contrasting the results obtained from such a series of studies, greater ecological validity and control of confounding variables could be achieved.

Neuro-Anatomical Model for Impaired Temporal Order
Processing

The results of this study were partially consistent with the findings of Tallal (1980), May et al. (1988), and Brannan and Williams (1988), in that dyslexics were found to

be impaired in processing of rapidly presented sequences of non-verbal stimuli. Yet, comparison of the results of these previous studies with those obtained in this investigation raises the question of whether dyslexics's deficits in processing temporal order information are modality-specific or are across all modalities. Mishkin's (1991) multiple-stage theory of learning and memory provides a vehicle for addressing this question.

Mishkin (1991) has theorized that each modality is specialized for processing and recognition memory, and that information related to stimulus features (i.e., length of a line or frequency of a tone) is sequentially processed through the primary, then secondary, and finally the tertiary cortical areas of each modality. Further, for all modalities, the final stage of processing stimulus features occurs in the same neuro-anatomical region, the temporo-insular region. Thus, within the context of Mishkin's model, impaired temporal order processing in dyslexics could be modality-specific (the lesion occurs in the primary, secondary and/or tertiary cortices), or could be across all modalities (the lesion occurs in the temporo-insular region).

Interpretation of the results of autopsy and neuroimaging studies within the context of Mishkin's (1991) model suggests that dyslexics have processing deficits which are both modality-specific and across all modalities. An

autopsy study of the brains of dyslexics found small cells within those layers of the lateral geniculate nucleus which are part of the magnocellular or transient visual system (Livingstone, Rosen, Drislane, and Galaburda, 1991). Since processing at the level of the lateral geniculate nucleus occurs prior to processing at the level of the primary visual cortex, this suggests that the processing deficits observed in dyslexics are modality-specific.

In contrast, the results of another autopsy study (Rosen, Galaburda & Sherman, 1986) and a neuroimaging study conducted by Hynd, Semrud-Clikeman, Lorys, Novey & Eliopoulos (1990) suggest that, the processing deficits observed in dyslexics are across all modalities. Both studies found symmetry or reversed asymmetry in the size of the planum temporale of dyslexics. Since, in non-dyslexics, the planum temporale in the left hemisphere is frequently larger than the analogous area in the right hemisphere, these results suggest that the planum temporale in the left hemisphere of dyslexics is smaller than normal (i.e., has less cell bodies than normal). This is of interest because the planum temporale is consistent with the temporo-insular region identified by Mishkin (1991) as the final area of processing stimulus features for all modalities.

That this study found dyslexics to be impaired in processing both auditory and visual temporal order information is suggestive of dysfunction in the temporo-

insular region, and therefore, of deficits in processing temporal order information across modalities. However, in order to determine whether dyslexics exhibit processing deficits across modalities or just within specific modalities, additional investigations of both visual and auditory processing in the same group of dyslexics are needed, rather than single modality investigations of cognitive processing which have constituted the majority of studies investigating the nature of dyslexia. Further, if the processing deficit is across modalities rather than modality-specific, more modalities than just auditory and visual should be affected. Therefore, these investigations should assess the dyslexics's ability to process tactile temporal order information as well.

Biological Model for Impaired Temporal Order

Processing in Dyslexics

In addition to providing anatomical evidence for abnormalities in the brains of dyslexics which might be the basis for processing deficits, Rosen et al. (1986) considered the etiological basis for these anatomical abnormalities, and therefore, by inference, for these cognitive processing deficits. They found ectopia (misplaced neurons) and dysplasia (anomalies of neuronal growth) in the perisylvian (also consistent with the temporo-insular region) and frontal regions of the brains of dyslexics at autopsy. The nature of these anomalies,

coupled with their being located in areas of the brain which are believed to be the last to complete cortical migration, suggested that they were caused by difficulties during the period of neuronal migration (20-28 weeks gestational age). However, there are other processes of neuronal development which, if affected, could result in ectopia.

Indeed, one such alternative explanation may be found in Hatten's (1990) *in vitro* investigations of neuronal migration. Her studies suggest that there is a common mechanism for neuronal migration throughout the brain such that glial fibers serve as a generic guide for locomotion and specific navigational instructions for migration are coded by the neurons themselves. Within this model, defects in neuronal migration would be related to genetic defects in the migrating neurons, not in the glial cells themselves. This suggests that the insult is occurring to the developing brain during the period of cellular proliferation, which occurs from the second week gestation age to around 6 months gestational age, rather than during cellular migration.

Secondary Hypothesis

Even though the validity of the post-hoc analysis of the dyslexics's performance on the visual and temporal order tests was affected by decreased power and the increased alpha error associated with the additional post-hoc testing, these results are of interest for their possible contribution to the investigation of whether or not dyslexia

is a heterogeneous disorder. Specifically, can dyslexics who are subgrouped according to the presence or absence of temporal order processing deficits be distinguished from each other on the basis of their performance on another measure of literacy skills?

In this post hoc analysis, dyslexics who had no deficits or only modality-specific deficits in temporal order processing could not be distinguished from each other on the basis of their spelling performance. However, dyslexics who had impairments in processing both auditory and visual temporal order information made fewer correct spellings and fewer good phonetic approximations of words they could not decode, or that they could not decode fluently, than did dyslexics who had no impairment in either auditory or visual temporal order processing. Overall, these results suggest that dyslexics may be distinguished on the basis of the presence or absence of temporal order processing deficits across modalities. Thus, suggesting that dyslexia is a heterogeneous disorder. Further, it may be that the dyslexics with deficits across all modalities are more severely impaired in their acquisition of literacy skills than dyslexics without such impairment. However, these results need to be replicated in a larger sample of dyslexics.

In any such replication a different measure of spelling achievement should be employed. A major drawback to using

the BTRSP as an experimental measure is that it is not standardized. Further, the determination of the dictated spelling list for each child is very subjective. Spelling words are selected from the list of words that the child is unable to decode or is dysfluent in decoding. Since each child did not make the same errors or dysfluencies, it is conceivable that each child in the study could have been administered a different spelling list. Further, as noted previously, the scoring of good phonetic equivalents is subjective. Therefore, it would seem more appropriate to use a standardized spelling test which employs standard, separate lists of phonetic and non-phonetic words and in which words are simply scored as correct or incorrect.

Limitations of this Study and the Direction of Future Research

The complete administration of the experimental measures required approximately 1 hour and 20 minutes. Even though their administration was divided across two sessions, the second session was dedicated entirely to the administration of experimental measures. Consequently, maintaining motivation to perform was an area of difficulty. This difficulty could be at least partially ameliorated by shortening the duration of the experimental protocol. The number of trials in each measure could be decreased. In addition, or alternately, the discrimination and closure tests could be eliminated from the protocol as they were not

helpful in discriminating the dyslexics from both groups of normal readers.

Based on the results of this investigation, a logical future experimental question would be "Do dyslexics exhibit deficits in processing temporally related information within all modalities?". To investigate this question, a tactile temporal order processing test would be added to the test battery. Since this future study would be the beginning of a systematic and methodical investigation of temporal order processing deficits in dyslexics, stimuli for these experimental measures would be selected from the bottom of a hierarchy of stimuli which range from non-verbal stimuli (low ecological validity with reading) to letters or words (greater ecological validity with reading). Consequently, these tests would again be composed of sequences of two individual non-verbal stimuli. In order to continue to employ an index group for which an assumption of homogeneity across studies could be made, subject criteria consistent with Morrison and Siegel's (1991) operational definition of dyslexia would again be employed.

Table 1

Subject characteristics

VARIABLE	GROUP						F	p
	DYSLEXIC N = 29 91% Male		CA CONTROL N = 49 51% Male		RA CONTROL N = 17 71% Male			
	MEAN	SD	MEAN	SD	MEAN	SD		
AGE (Mos) ■	100.93	9.46	103.47	9.9	85.12	6.69	25.37	<.001
WRAT-R Reading Raw Score ✓	39.48	6.31	64.59	7.47	41.53	7.51	138.35	<.0001
WRAT-R Reading Standard Score ✓	69.00	7.09	103.86	10.07	93.65	5.75	150.41	<.0001
PPVT-R	99.97	12.75	101.94	14.59	105.88	16.12	.91	.40
Raven's Coloured Progressive Matrices	94.93	11.46	99.96	9.82	100.47	9.68	2.53	.09
Parent Hyperactivity Index	.96	.58	.79	.57	.65	.38	1.84	.16
Teacher Hyperactivity Index □	.67	.55	.20	.37	.48	.50	9.94	<.001

- Dyslexic = CA control > RA control; Tukey HSD, p < .05
- ✓ CA control > Dyslexic = RA control; Tukey HSD, p < .05
- ✓ CA control > RA control > Dyslexic; Tukey HSD, p < .05
- CA control = RA control < Dyslexic; Tukey HSD, p < .05

Table 2

Relationship between experimental measures and age ■

Variable	r	Significance	r square
Auditory Closure	0.29	.004	0.08
Auditory Discrimination	0.25	.015	0.06
Auditory Temporal Order	0.34	.001	0.12
Visual Closure	0.31	.002	0.10
Visual Discrimination	0.32	.002	0.10
Visual Temporal Order	0.24	.022	0.06

■ Chance scores substituted for missing scores (N = 95)

Table 3

Discriminant function analysis results for experimental measures using z-scores for total correct

Between Groups	Predictor Variables	Wilk's Lambda	Significance	Predicted Group Membership	% Correctly Classified
Dyslexic (N = 29) vs. CA control (N = 49)	Vis. Temporal Order	.82	.0001	DYSLEXIC - 55% CA Controls-84%	73
	Aud. Temporal Order	.79	.0002		
	Vis. Closure	.78	.0003		
Dyslexic (N = 29) vs. RA control (N = 17)	Vis. Discrimination	.88	.02	DYSLEXIC - 93% RA Controls-47%	76
	Vis. Temporal Order	.84	.03		
	Aud. Closure	.79	.02		
	Aud. Temporal Order	.76	.02		
RA control (N = 17) vs. CA control (N = 49)	Vis. Discrimination	.79	.0001	RA Controls-41% CA Controls-88%	76
	Aud. Closure	.76	.0002		

Rotated factor matrix using z-scores and
no substitution of missing data (N = 56)

<u>Variable</u>	<u>Factor 1</u>	<u>Factor 2</u>
Auditory Closure	.72	.03
Auditory Discrimination	.79	.07
Auditory Temporal Order	.77	.09
Visual Closure	.61	.37
Visual Discrimination	.06	.79
Visual Temporal Order	.11	.70

FIGURE CAPTIONS

Figure 1. Sine-wave gratings, which vary in spatial frequency, employed as stimuli in spatial frequency analysis.

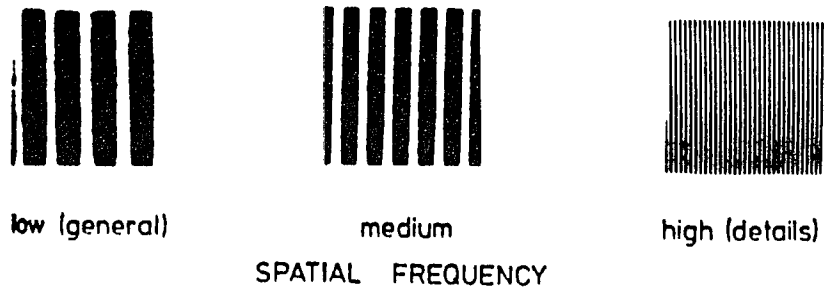
Figure 2. Breitmeyer's theorized model of functional interaction between the sustained and transient visual systems to produce clear pattern vision.

Figure 3. Group x Process interaction resulting from three-way mixed ANOVA.

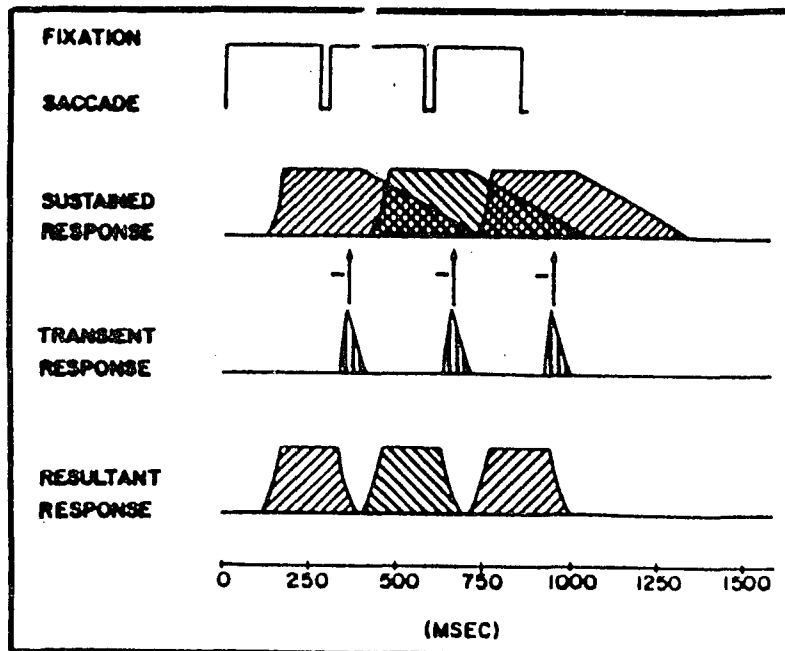
Figure 4. Group x Process interaction resulting from three-way mixed ANOVA when the data for males only was analyzed.

Figure 5. Group x Speed interaction resulting from three-way mixed ANOVA.

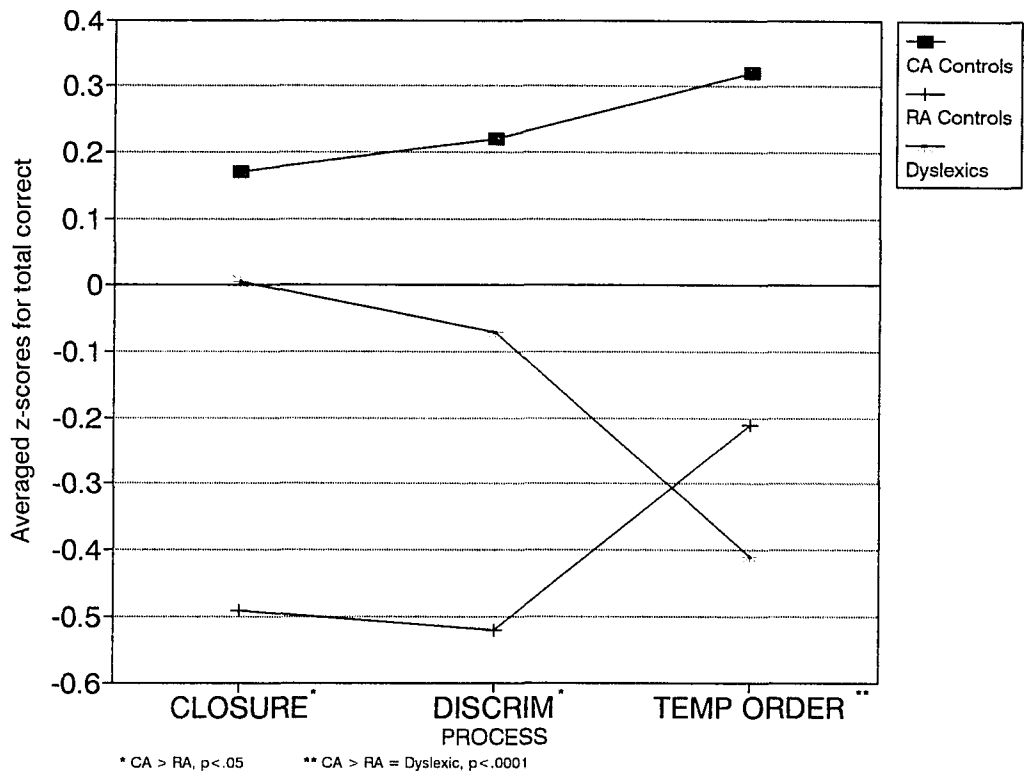
Figure 6. Results of one-way ANOVA comparing derived groups of dyslexics on their ability to correctly spell, or spell with good phonetic approximation, words which they could not read or had difficulty reading. The derived groups were based upon impairment or lack of impairment in auditory and/or visual temporal order processing.

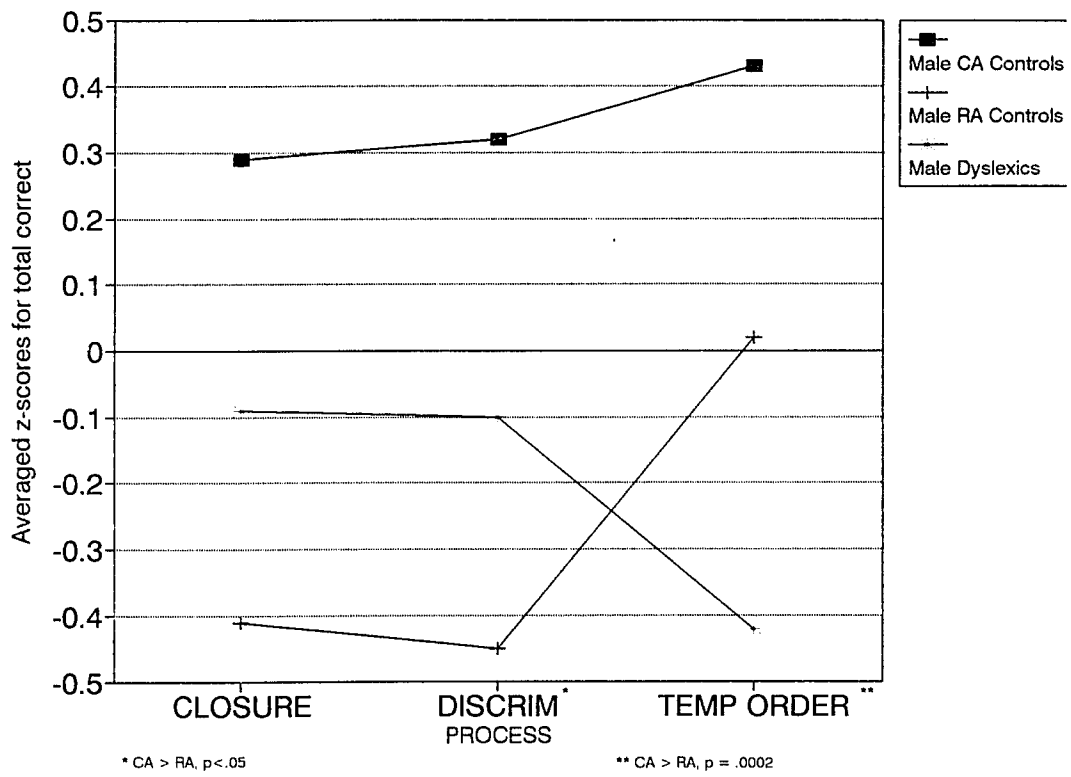


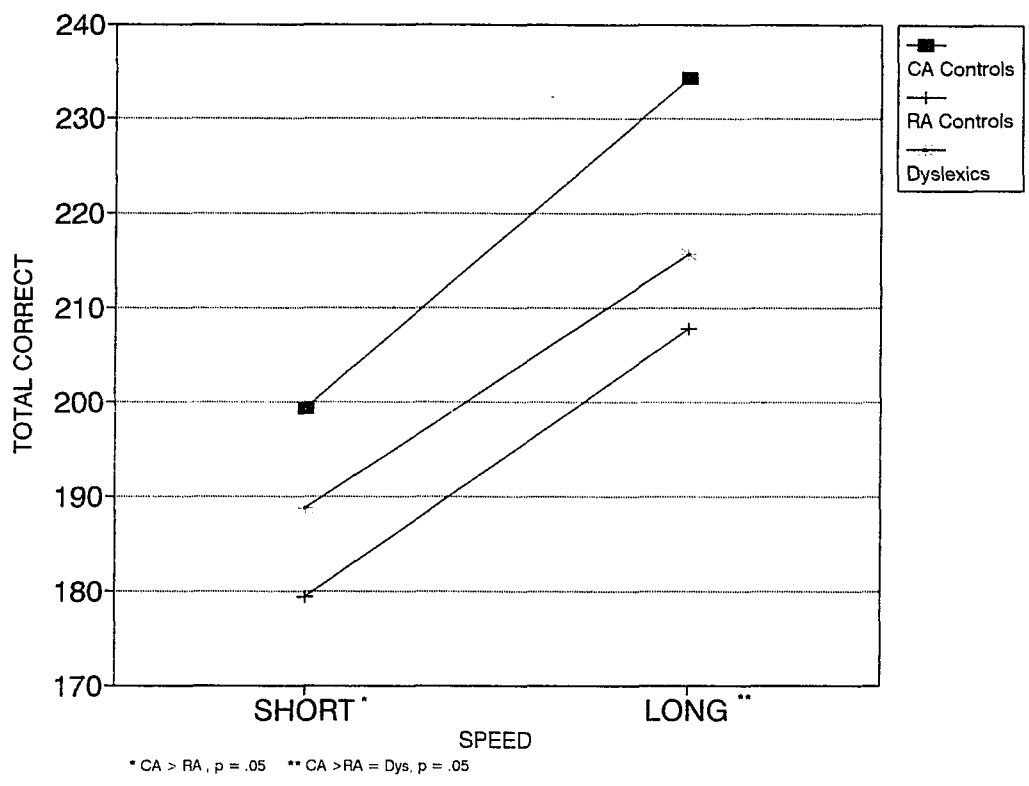
Note. From "A Theoretical and Experimental Case for a Visual Deficit in Specific Reading Disability" by W. Lovegrove, F. Martin and W. Slaghuis, 1986, Cognitive Neuropsychology, 3 (2), p. 225-267. Copyright 1986 by the Lawrence Erlbaum Associated Limited. Reprinted by permission.

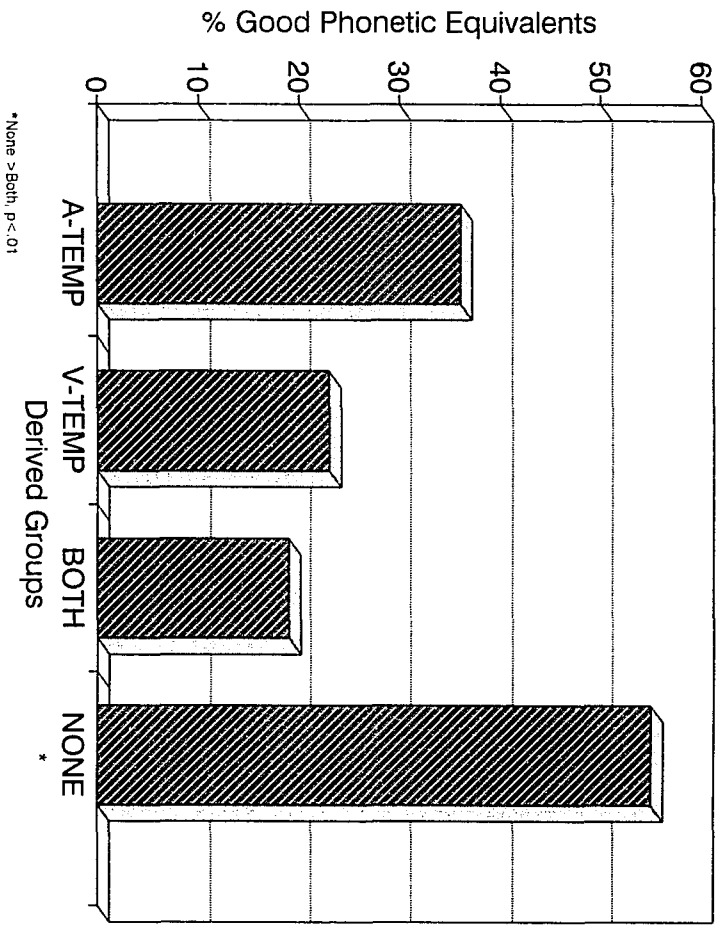


Note. From "Unmasking Visual Masking: A Look at the "Why" Behind the Veil of the "How" by B. G. Breitmeyer, 1980, *Psychological Review*, 87 (1), p. 52-69. Copyright 1980 by the American Psychological Association, Inc. Reprinted by permission.









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