A MULTIVARIATE INVESTIGATION OF THE TIMING DEFICIT HYPOTHESIS OF READING DISABILITY

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This thesis presents a multivariate investigation of the temporal processing deficit hypothesis of reading failure. The temporal processing deficit hypothesis proposes that the underlying cause of the phonological deficit that characterizes developmental dyslexia is an impaired timing mechanism. Thirty reading-disabled adults, thirty two normally achieving adults and thirty one normally achieving children were administered a comprehensive battery that included a wide range of timing tasks, in addition to reading and phonological measures. Although dyslexics performed more poorly than normally achieving adults on most of the timing tasks, their performance was not influenced by rate. Similarly, although the dyslexics' performance revealed the typical pattern of impaired phonological awareness and pseudoword reading relative to reading level matched children, the disabled readers outperformed the children on the timing tasks. Finally, with the exception of RAN performance, the timing tasks shared little variance with phonological awareness and contributed little unique variance to word reading. Although these findings undermine the timing deficit hypothesis, they do provide evidence for the involvement of word retrieval deficits in developmental dyslexia.

for my husband, Dan

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General Statement

It is well established that developmental dyslexia is characterized by deficient phonological processing (e.g., Bruck & Treiman, 1990; Rack, Snowling, & Olson, 1992; Perfetti, 1985; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). However, it is unclear what mechanism underlies the phenotypic core deficit of reading disabilities. One hypothesis that has attracted growing attention is known as the temporal processing deficit of developmental dyslexia (e.g., Farmer & Klein, 1995; Tallal, 1984; Wolff, Michel & Ovrut, 1990a, 1990b). This theory posits that an impaired timing mechanism underlies the phonological phenotypic performance profile of dyslexia, through deficient temporal resolution. Although the temporal processing deficit theory has strong advocates, such as Tallal (1980, 1984), its critics include researchers such as Studdert-Kennedy (Studdert-Kennedy & Mody, 1995). In the face of such controversy, the need has arisen for external examination of the temporal processing deficit--that is, for its examination within laboratories other than those that have been at the center of the controversy. Therefore, the purpose of this thesis is to examine the validity of the temporal processing deficit hypothesis of developmental dyslexia. This endeavor involves both a critical examination of the literature and the empirical investigation of hypotheses generated from the temporal processing deficit hypothesis.

Introduction

A basic concept in the field of learning disabilities is that individuals with developmental dyslexia share a common phenotypic performance profile. This profile is characterized by a deficit in phonological processing, particularly in phonological awareness (e.g., Jorm & Share, 1983; Stanovich, 1988; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). Phonological awareness refers to one's direct knowledge of phonemes, as evidenced in the ability to recognize and manipulate phonemes (Bentin, 1992; Liberman, Shankweiler, Fisher & Carter, 1974;

Tunmer & Hoover, 1992). A variety of tasks have been used to assess phonological awareness, requiring children to generate rhymes, count phonemes and syllables, substitute phonemes and delete phonemes (Høien, Lundberg, Stanovich & Bjaalid, 1995). These tasks typically reveal dyslexics' difficulties in phonological processing (*e.g.*, Bowey, Cain & Ryan, 1992; Wagner & Torgesen, 1987). For example, dyslexics tend to be less sensitive to rhymes (Snowling, van Wagtendonk & Stafford, 1988), and alliterations than normal readers (Bradley & Bryant, 1983). Dyslexic children also tend to experience great difficulties in segmenting speech (Bruck 1990, 1992; Bryant, Bradley, MacLean & Crossland, 1989; Mann, 1984; Olson, Wise, Conners, Rack, & Fulker, 1989; Snowling, Stackhouse & Rack, 1986; Stanovich, 1988; Stanovich & Siegel, 1994). These deficits are evident even when the performance of dyslexics was compared to that of younger children who read no better than they did (Bradley & Bryant, 1983; Bruck, 1992; Olson et al., 1989). Because the performance of older, disabled readers is inferior to that of younger, skilled readers, one may infer that the poor performance resulted from a specific deficit, rather than uniformly slower maturation of reading skills (Bryant & Goswami, 1986; Felton & Wood, 1992). Thus, the performance profile of disabled readers tends to support a deficit model, rather than a maturational lag model.

There is growing evidence that phonological awareness plays an important role in early reading acquisition (Bradley & Bryant, 1983; Cunningham, 1990; Goswami & Bryant, 1990; Lundberg, Frost & Peterson, 1988; Perfetti, 1984). In fact, phonological awareness is often a more powerful predictor of the speed and efficiency of reading acquisition than more general factors of cognitive functioning such as measures of general intelligence, vocabulary and listening comprehension (Share, Jorm, Maclean & Matthews, 1984; Stanovich, 1992; Stanovich, Cunningham & Cramer, 1984; Stanovich, Cunningham & Feeman, 1984). Impaired phonological awareness is considered an important precursor to deficits in phonological coding, the process whereby letter patterns are converted into phonological patterns (Stanovich, 1991). Because appreciation of the alphabetic principle, that units of print map onto units of sound (see Perfetti, 1984), is dependent on the ability to segment speech at the phonemic level, poor phonological awareness impairs the acquisition of grapheme-phoneme correspondences that underlie fluent word recognition (Goswami & Bryant, 1990; Stanovich et al., 1984; Tunmer & Hoover, 1992). Deficits in phonological coding are characterized by difficulty in naming pseudowords (Rack et al., 1992). In fact, deficits in naming pseudowords is the most diagnostic symptom of reading disability (Bruck, 1988, 1990; Felton & Wood, 1992; Manis, Custodio & Szeszulski, 1993; Siegel, 1989; Siegel & Ryan, 1988). Dyslexic children not only name pseudowords less successfully than chronological-age controls, but they are less successful than younger, reading-level matched children (Olson et al., 1989; Rack et al., 1992; Stanovich & Siegel, 1994). Deficits in phonological coding, revealed through impaired pseudoword naming has important implications for reading acquisition. The recognition of unknown words through phonological coding is required for a child to gain independence in reading. Reading independence, in turn, will enable the child to practice reading so that he or she may attain the automaticity necessary for fluent reading (Ehri & Wilce, 1985; Jorm & Share, 1983). Therefore, deficits in phonological awareness interrupts the very processes necessary to develop fluent reading.

While phonological awareness is predictive of subsequent skill at word-reading (e.g., Adams, 1990; Bryant et al., 1989; Bruck & Treiman, 1990; Stanovich et al., 1984; Wagner, Torgesen, & Rashotte, 1994), the relationship between the two is one of reciprocal causation (Ehri, 1985; Morais, Bertelson, Cary, & Alegria, 1979; Vandervelden & Siegel, 1995). That is, not only does phonological awareness contribute to reading acquisition, reading acquisition itself encourages further development of phonological awareness. Due to the reciprocal relationship between phonological awareness and reading skill, individuals with developmental dyslexia may have similar, yet not identical, phenotypic performance profiles that result from different causes. Thus, the root of reading failure for some individuals lies in their impaired phonological processing. Alternately, for other individuals, poor word reading skills result in poor performance on tasks tapping phonological awareness. These patterns may reflect the two subtypes of dyslexia that have been suggested in the literature, phonological and surface dyslexia. Surface dyslexia is characterized by the ability to read aloud regular words and pseudowords, but not irregular words (Behrmann & Bub, 1992; Boder, 1973; Coltheart, Masterson, Byng, Prior & Riddoch, 1983). In contrast, phonological dyslexia is characterized by the ability to read familiar words, but not pseudowords (Beauvois & Derousesne, 1979; Boder, 1973; Shallice & Warrington, 1980; Temple & Marshall, 1983). These patterns of performance have often been used as an explanation of the cause of reading disability. For example, because phonological dyslexics experience great difficulty in reading unfamiliar words and pseudowords, an inability to apply grapheme-phoneme correspondence rules might be assumed to be the cause of reading failure. In contrast, because surface dyslexics experience difficulty in reading irregular words, an impaired ability to form orthographic representations might be the cause of reading failure. However, although surface dyslexics' primary problem may lie in the formation of orthographic representations, they also have some degree of a phonological processing deficit.

Although many studies supporting the existence of the two subtypes of developmental dyslexia have been controversial due to their failure to include normal readers as a reference group (see Bryant & Impey, 1986), Castles and Coltheart's (1993) study was unique in its attempt to avoid this criticism. In their analyses, Castles and Coltheart isolated a large number of dyslexics whose performance profiles were deviant (relative to normal readers) on either nonword or exception word reading. These patterns represent the two distinct subtypes of phonological and surface dyslexia. However, a serious criticism of this study is the failure to include a reading-level matched control group. Fortunately, this problem has been addressed (see Manis, Seidenberg, Doi, McBride-Chang, & Patterson, in press; Sidhu, 1995; Stanovich, Siegel, Gottardo, Chiappe, & Sidhu, in press). In each of these studies, a large number of phonological and surface dyslexics were identified when referenced against chronological-age matched subjects. Although a large number of phonological dyslexics were identified when a reading level match was used, few surface dyslexics were identified. This converges with Bryant and Impey's ability to find a match in their reading-level sample for the performance patterns of Coltheart et al.'s (1983) surface dyslexic, but not Temple and Marshall's (1983) phonological dyslexic. Thus, phonological dyslexia appears to represent a pattern of deviance, while surface dyslexia appears to be consistent with the maturational lag model. Therefore, if one were searching for an underlying deficit which is manifested as the phonological core deficit, one would expect to find it among phonological dyslexics, but not surface dyslexics.

Recall that impaired phonological processing, often known as the phonological core deficit, refers to the phenotypic performance profile of individuals with reading disabilities. The phonological core deficit may be considered a proximal cause of developmental dyslexia because it provides a causal explanation for reading disability at a psychological, or more specifically a cognitive level. In contrast, explanations that attempt to characterize developmental dyslexia at a neurophysiological level (*e.g.*, Hynd, Marshall & Gonzalez, 1991; Larsen, Høien, Lundberg & Odegaard, 1990; Steinmetz & Galaburda, 1991) appeal to more distal causes of reading disability. That is, they attempt to explain how the structure and functioning of the brain underlie deficits in phonological processing and reading failure. Similarly, investigations of the genetics of dyslexia also invoke more distal explanations for reading failure and the phonological core deficit (*e.g.* Olson et al., 1989; Pennington, Gilger, Olson & DeFries, 1992). Thus, the reading disability may be explained at a variety of levels.

The current thesis investigates a hypothesis that may be considered an intermediate causal explanation for reading failure. This hypothesis, known as the temporal processing deficit or timing deficit hypothesis, proposes that impaired phonological processing and reading failure results from impaired temporal processing. This hypothesis will be considered in greater detail below. However, it is important to note here that although the timing hypothesis presents an explanation that is psychological (as it generates clear predictions concerning the information-processing operations that underlie reading failure), this explanation is one level more distal than the phonological core. Therefore, the timing hypothesis does not attempt to undermine or replace the phonological-core deficit as a causal explanation for developmental dyslexia. Rather, it attempts to provide a complementary explanation by invoking a psychological mechanism that <u>underlies</u> the phonological core deficit.

What is the Timing Hypothesis?

Recently, the hypothesis that developmental dyslexia is caused by an underlying deficiency in temporal processing has attracted growing attention. A number of theorists have proposed that an impaired timing mechanism involved in the temporal organization of perception and/or action is the cause of reading failure within some subtypes of developmental dyslexia (e.g., Farmer & Klein, 1995; Tallal, 1984; Wolff et al., 1990a, 1990b). The mechanism involved in temporal processing is assumed to be responsible for a variety of functions such as the timing precision, serial order, and rate. The function of timing precision enables individuals to perform actions at accurate intervals. Similarly, it enables individuals to perceive rhythmic sequences. The function of serial order involves the perception, recognition and recall of the temporal sequence in which stimuli were presented, and the production of a number of actions in the correct sequence. Finally, the function that has garnered the most attention, namely rate, refers to one's skill at rapid processing. Rapid processing includes both the perception of rapidly presented stimuli and the rapid coordination of actions. Although proponents of the temporal processing deficit hypothesis propose different manifestations of a timing mechanism (i.e., is this mechanism specific to a single domain, such as audition, or is it domain-general?), all agree that impaired temporal processing underlies the phonological core deficit that is characteristic of developmental dyslexia. These theories will be considered below.

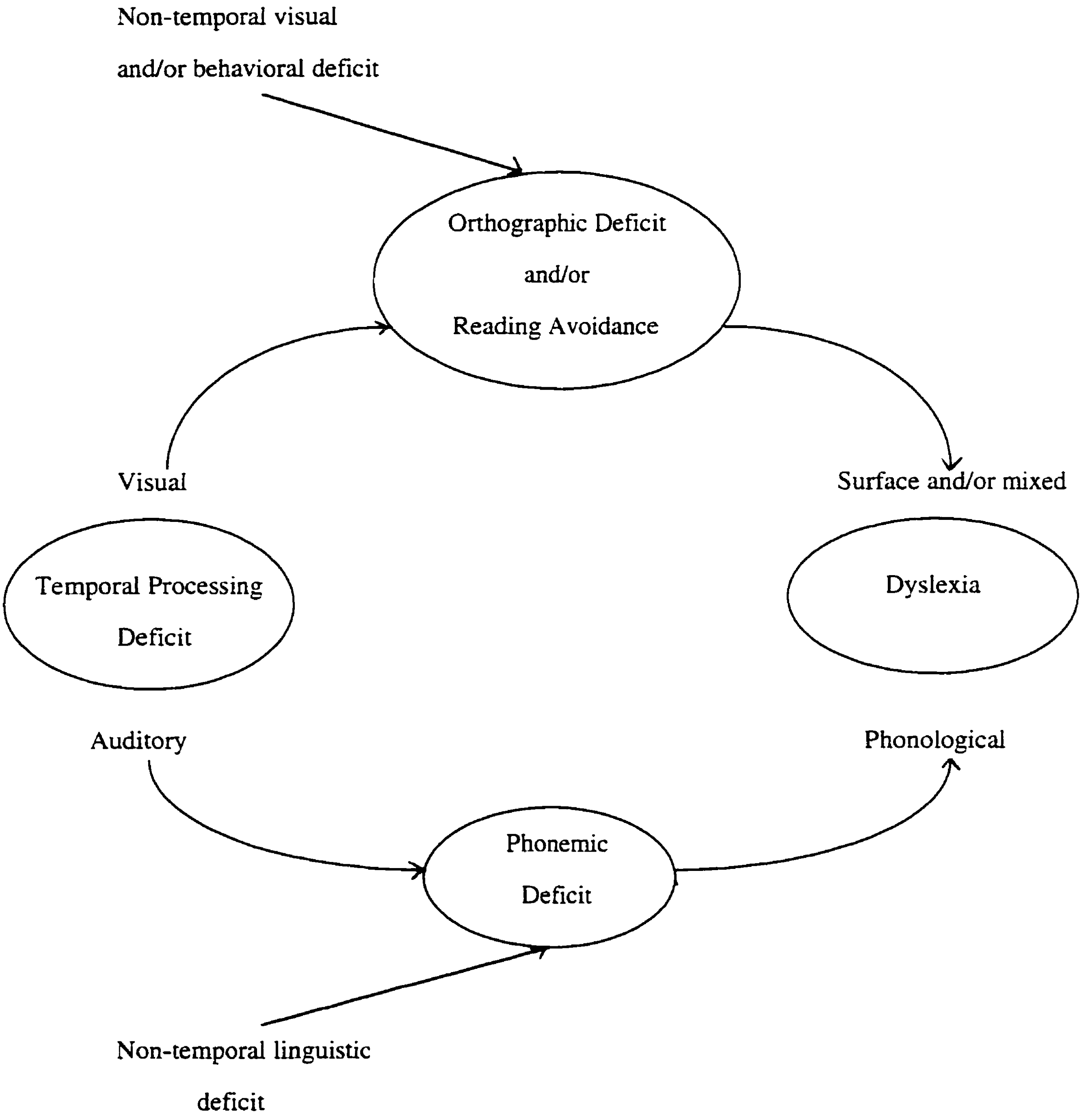
The initial, and most influential of the "timing" theories is that of Tallal (1980; 1988; Tallal & Stark, 1982). Tallal has proposed that disabled readers are deficient in processing auditory stimuli that are very brief (*i.e.*, tens of milliseconds), whether the stimuli are verbal or nonverbal in nature. Some speech sounds, such as stop consonants like /b/ and /d/, involve spectral changes with durations that lie within this critical period of tens of milliseconds. According to Tallal, the combination of disabled readers' deficient processing of rapidly presented stimuli and the brevity of the spectral changes within speech sounds results in an inability to discriminate speech sounds. This rapid temporal processing deficit may subsequently lead to reading failure in two ways. First, inadequate skill at discriminating phonemes would lead to the poor phonemic awareness and segmentation skills that characterize the phenotypic profile of dyslexia. In other words, the temporal processing deficit underlies the phonological core deficit. Alternately, the poor discrimination of speech sounds would impede the acquisition of phoneme-grapheme correspondences necessary for normal development of reading skills.

Tallal's theory of the temporal processing deficit primarily restricts the impairment to the auditory modality. However, more recently Farmer and Klein (1995), have proposed that the temporal processing deficit is more pervasive, as it may manifest itself in a variety of modalities. For example, Farmer and Klein's (1995) model of the pathways by which a temporal processing deficit may lead to dyslexia supplements the auditory processing deficit with a visual processing deficit. Their model is depicted in Figure 1. In this model, the mechanism by which the auditory processing deficit manifests itself as dyslexia is based on the mechanism proposed by Tallal (1984). That is, the auditory processing deficit both causes impoverished phonological awareness and inhibits the acquisition of phoneme-grapheme correspondences. Similarly, the visual processing deficits may lead to reading failure in two ways. On the one hand, impaired visual temporal processing may directly impede the acquisition of orthographic representations. A slower rate of processing may cause the processing of visual stimuli to be incomplete, which consequently impairs perception (Di Lollo, Hanson & McIntyre, 1983). On the other hand, impaired visual temporal processing might hinder reading acquisition indirectly, by making reading a difficult and unpleasant activity (Farmer & Klein, 1995). Poor readers with this affliction would likely avoid reading, causing them to be prone to the Matthew Effects discussed by Stanovich (1986b). Thus, Farmer and Klein (1995) have proposed that impaired temporal processing in the auditory or the visual domain may result in reading failure.

According to Farmer and Klein, the temporal processing deficit may be either domain-specific or domain-general. Their model suggests that it is possible for the temporal processing deficit to exist in either the visual or the auditory modality, or for there to be independent temporal processing deficits within each modality. However, a final possibility is the existence of a domain-general temporal processing deficit that interferes with both visual and auditory

Figure 1:

Farmer and Klein's (1995) model of the potential pathways to dyslexia from a temporal processing deficit in either the auditory or the visual modality (p.481).



perception. Proponents of a domain-general timing mechanism have proposed that this mechanism is involved in the temporal organization of action in addition to perception (e.g., Tzeng & Wang, 1984; Wolff et al., 1990a, 1990b). That is, individuals afflicted with this disorder would be expected to show impaired performance on all activities involving fine temporal resolution, whether the tasks entail perception, motor coordination, or speech production. Thus, a defective domain-general timing mechanism would involve serious consequences, as such an impairment would result in pervasive impairments. For example, Nicolson and Fawcett (1990; Fawcett & Nicolson, 1992) have reported that disabled readers were impaired in postural control, or balance, particularly when they had to perform a second simple task concurrently. Yap and van der Leij (1994) confirmed the finding that dyslexics have difficulties in balancing when performing a concurrent task. The apparent deficits in "automatic" balance reflects one of the global deficits that may result from a defective domain-general timing mechanism.

The proposal of a defective mechanism that causes global impairment violates the assumption of specificity, that the cause of reading disability is localized in a specific cognitive domain rather than more global aspects of cognitive functioning (Stanovich, 1986a, 1988). Should the underlying cause of reading disability be an impaired domain-general timing mechanism, one would expect performance in all aspects of motor and intellectual functioning to be depressed. Such pervasive impairment would result in diminished performance on tests of intelligence so that dyslexics would not be able to have high IQ scores. However, the phonological deficit that characterizes dyslexia is only weakly correlated with intelligence (McBride-Chang & Manis, 1996; Siegel, 1988, 1989; Stanovich, 1986b; Tunmer & Nesdale, 1985; Vellutino & Scanlon, 1987). Therefore, if a deficient domain-general timing mechanism is the underlying cause of the phonological deficit that characterizes developmental dyslexia, it must be able to account for the weak relationship between intelligence and phonological processing.

In summary, there are four main approaches to the timing deficit hypothesis of developmental dyslexia. These theories differ primarily in the breadth attributed to the mechanism involved in temporal resolution. The first, and most restricted hypothesis suggests that impaired temporal resolution in the auditory modality, alone, is the underlying cause of the phonemic deficit characteristic of developmental dyslexia (e.g., Tallal, 1984). The second hypothesis proposes that defective temporal resolution in the auditory or visual modality is the underlying cause of reading failure. These impairments may be the results of a single defective timing mechanism, or defective timing mechanisms within both modalities (e.g., Farmer & Klein, 1995). The third hypothesis advocates a defective domain-general timing mechanism as the root of developmental dyslexia (e.g., Wolff et al., 1990b). This hypothesis predicts the most pervasive impairments, manifested in perception, speech and action. Finally, opponents of the timing hypothesis (e.g., Studdert-Kennedy & Mody, 1995) argue that there is little evidence to support the existence of a temporal deficit and its role in developmental dyslexia. Support for each position will be examined below.

Evidence Regarding Auditory Temporal Processing Deficits in Developmental Dyslexia

The approach that will be explored here is the plausibility that the phonemic deficit associated with developmental dyslexia is a symptom of an underlying auditory processing deficit (Tallal, 1984). The first, and most influential advocate of this position is Paula Tallal. According to Tallal (1980), the ability to process rapidly changing auditory information plays a crucial role in speech perception. Difficulties in processing rapidly presented data may result in difficulties in analyzing speech at the phonemic level and the phonological deficit exhibited by some dyslexics may be the product of deficient processing of rapid auditory stimuli. Such a deficit would impair the acquisition of grapheme-phoneme correspondences in a manner similar to that posited in phonological core deficit theories (Stanovich & Siegel, 1994). According to the auditory temporal processing deficit hypothesis, the role of phonological processing in reading acquisition can be explained by phonological core deficit theories because the auditory temporal processing deficit hypothesis proposes a more distal explanation for reading failure than the phonological processing deficit.

Two sources of evidence are needed to support Tallal's theory. First, one must demonstrate that children with developmental dyslexia process rapidly presented stimuli more poorly than normal readers. Second, one must demonstrate that this deficit is primarily auditory, and not specific to speech. This is exactly what Tallal (1980) demonstrated in her comparison of reading disabled and chronological age-matched children. In this study, a series of discrimination and temporal order judgment (TOJ) tasks was administered to children. The stimuli, two complex tones presented for 75 ms, were separated by a long (428 ms) or a short (8-305 ms) interstimulus intervals (ISI). Tallal found no difference between normal and disabled readers when the tones were presented at slow rates. However, when the ISI was shortened, disabled readers made significantly more errors than normal readers. In fact, Tallal found that the Spearman Rank Correlation between performance on auditory perceptual tasks and a pseudoword reading task was quite high (r=.81). This general pattern of results has been replicated by Reed (1989). These findings have been interpreted as support for the existence of impaired auditory temporal processing in disabled readers (e.g., Farmer & Klein, 1995).

In addition to studies investigating disabled readers, evidence for impaired temporal processing deficits has also been drawn from studies investigating auditory discrimination skills of dysphasic children. In a series of studies examining auditory discrimination in dysphasic children and normal readers (Tallal & Piercy, 1975; Tallal, Sainburg & Jernigan, 1991), Tallal and her colleagues used as stimuli pairs of long and short tones, pairs of long (250 ms) and short (43 ms) synthetic vowels, and pairs of synthetic CV syllables (/ba/ and /da/) in which the formant transitions were either long (95 ms) or short (43 ms). The dysphasic children's performance was significantly worse than the nondisabled children on the short tones, vowels and consonants at short ISIs, but not on the long tones, vowels and consonants at long ISIs. Like the dyslexic children, dysphasic children showed a pattern of poor discrimination of auditory stimuli at fast speeds, but not at slow speeds. Because dysphasics showed the same pattern of results for both steady-state vowels and the consonants (which contain formant transitions), Tallal and Piercy (1975) concluded that impaired performance reflected the brevity and not the transitional traits of the synthesized stimuli. Similarly, the parallel pattern of results for syllables and tones has lead Tallal and Piercy (1973) to conclude that the dysphasics' impairment was a general auditory deficit. Because dysphasic children's performance was similar to that of disabled readers, these findings have often been generalized as evidence for auditory temporal processing deficits in developmental dyslexia, particularly in recent media reports.

However, impaired auditory temporal processing is not the only possible interpretation that may arise from a pattern of impaired discrimination of fast, but not slow, auditory stimuli. In fact, Tallal (Tallal et al., 1991) has concluded that "the sequencing deficit identified in dysphasic children is a secondary sequelea due to the more primary deficit in tone discrimination of rapidly presented stimuli"(p. 365). In other words, what may appear to be a slower rate of perception (i.e., impaired performance at short but not long ISIs on perceptual tasks) is not the cause of impaired children's difficulties. It is the result of poor discrimination between the close phonetic similarity of the stimuli (Studdert-Kennedy, Liberman, Brady, Fowler, Mody & Shankweiler, 1994-1995; Studdert-Kennedy & Mody, 1995). Similarly, Reed (1989) has argued that the TOJ tasks enable the detection of subtle deficits in discrimination capacity by stressing perceptual capabilities. In other words, the performance of children who have difficulties discriminating stimuli (such as /ba/-/da/) would suffer when their capacities are stressed. In contrast, when the discrimination is easier, performance would not be expected to suffer when perceptual capacities are stressed.

Mody tested this alternative explanation by administering Tallal's TOJ task to poor readers in second grade (Mody, Studdert-Kennedy & Brady, in press). Children were first administered Tallal's TOJ task using the difficult to discriminate pair of syllables /ba/ and /da/. These children experienced difficulties discriminating these syllables when they were presented with short ISIs. However, using the same procedure with easily discriminable pairs of syllables, /ba/-/sa/ and /da/-/Sa/, Mody and her colleagues (in press) found that children performed perfectly even at short ISIs. These findings show that reading-disabled children's difficulties discriminating /ba/ and /da/ is not the result of impaired temporal processing or deficient processing of rapidly changing accoustic information. These results suggest that the impaired performance on Tallal's TOJ task arises from difficulties in discriminating between similar syllables that are presented in rapid succession. Therefore, disabled readers may perform poorly on TOJ tasks because the task is sensitive to subtle deficits in discriminating phonetically similar phonemes, rather than impaired auditory temporal processing, per se.

The Mody et al. (in press) findings suggest a basic confusion that recurs in each of the timing deficit theories, which is the confusion between the concepts of temporal perception and rapid perception (Studdert-Kennedy & Mody, 1995). Temporal processing refers to the perception of the temporal properties of events. These include the duration, sequencing, and rhythm of events. This contrasts with rapid perception, which refers to the ability to process rapidly presented stimuli. However, in the literature there is often confusion regarding the distinction between these concepts. Temporal perception is often equated with both sequential perception and the perception of rapidly presented stimuli. This distinction is important because performance on tasks involving the perception of rapidly presented sequences, such as Tallal's TOJ task, is also dependent on one's ability to process stimuli of brief duration. In other words, if one cannot discriminate between stimuli, one would be unable to report the order in which the stimuli were presented. Therefore, performance that appears to reflect impaired sequential performance may, in fact, "stem from a more primary perceptual deficit that affects the rate at which they can process perceptual information" (Tallal, 1980, p. 193).

Although it remains controversial whether Tallal's TOJ paradigm reveals auditory temporal processing deficits, or impaired discrimination of similar phonemes, other paradigms that are more clearly temporal in nature have revealed differences between normal and disabled readers. For example, McCroskey and Kidder (1980) found that reading disabled children required longer ISIs to detect a temporal gap between two identical tones. Another set of tasks involved complex judgments of rhythm. Note that judgments concerning rhythm may be considered exemplars of temporal processing (Studdert-Kennedy & Mody, 1995). Zurif and Carson (1970) demonstrated that dyslexics were inferior in processing auditory (and visually) patterned stimuli. Disabled readers performed significantly worse than normal readers on the Seashore auditory rhythm test (Halstead, 1947) and its visual analogue. This task requires subjects to judge if two rhythmic patterns tapped out in quick succession are the same. Performance on these temporal pattern discriminations correlated significantly with reading skill. In fact, performance on the auditory and visual versions of the Seashore rhythm test shared 29% to 34% of the variance, respectively, with word recognition. McGivern, Berka, Languis and Chapman (1991) replicated Zurif and Carson's (1970) findings with a younger sample of children. Thus, the Seashore Rhythm Test's successful discrimination between dyslexics and normal readers provides support for the association between rapid auditory temporal pattern recognition and successful reading.

In sum, the pattern of results yielded by Tallal's temporal order judgment task leads to equivocal interpretations. While they suggest disabled readers may suffer from auditory temporal processing deficits, impaired performance on TOJ tasks may stem from difficulties in discriminating between phonemes. However, studies that show that normal readers outperform reading-disabled children on gap detection and rhythm detection lend support to the temporal processing deficit hypothesis.

Evidence Regarding Visual Temporal Processing Deficits in Developmental Dyslexia

Like the existence of an auditory temporal processing deficit, the role of a visual temporal processing deficit in developmental dyslexia has proven to be controversial. A growing body of evidence suggests that in comparison to normal readers, disabled readers may have some underlying difficulty in visual perception (for reviews, see Willows, 1991; Willows, Kruk & Corcos, 1993). However, such a theory has proven to be controversial. For example, while researchers such as Lovegrove (Lovegrove, Martin & Slaghuis, 1986) have reported that 75% of disabled readers they had tested exhibited visual processing deficits, most other attempts at classification have found only 4 to 16% of the disabled readers had some type of visual, spatial or perceptual deficit (Rayner, Pollatsek & Bilsky, 1995). In order to evaluate these discrepant claims, one must first examine the tasks used to generate these conclusions.

The two types of paradigms have been used most often to determine whether normal and disabled readers differ in their speed of visual processing: temporal integration tasks and backwards masking tasks. Temporal integration tasks are used to assess visible persistence, or the length of time an item can still be perceived after the eye has ceased to fixate upon it (Coltheart, 1980). These tasks may involve the presentation of two identical stimuli in close temporal sequence (e.g., Lovegrove et al., 1986; O'Neill & Stanley, 1976), or the successive presentation of two different stimuli (e.g., Stanley & Hall, 1973). The minimum length of the ISI between the two stimuli that an individual requires to report that the stimuli are separate, the "separation threshold", reflects the duration of visible persistence for the first item (Willows, Kruk & Corcos, 1993). Using these procedures, a number of researchers have found evidence that visible persistence is significantly longer for disabled readers than non-disabled readers. For example, Lovegrove and his colleagues have demonstrated that children with specific reading disabilities required longer ISIs to detect a blank screen between two sine-wave gratings at low spatial frequencies than normal readers (Badcock & Lovegrove, 1981; Lovegrove, Heddle & Slaghuis, 1980; Lovegrove et al., 1986). In fact, the children's separation thresholds were found to be predictive of reading skill (Lovegrove, Slaghuis, Bowling, Nelson & Geeves, 1986). Converging evidence for longer visual persistence in reading-disabled children has been reported by a number of laboratories (e.g., Di Lollo et al., 1983; O'Neill & Stanley, 1976; Stanley & Hall, 1973).

While temporal integration tasks measure visible persistence, the other type of paradigm, backwards masking, measures the rate of information pick up in the early stages of information processing (Rayner & Pollatsek, 1989). Like the temporal integration task, two stimuli, the target followed by the mask, are presented in rapid succession. However, in backwards masking what is measured is the interval between the onset of the two stimuli (the stimulus onset asynchrony, or SOA) at which processing of the second stimulus no longer interferes with the processing of the first. Simply, a longer critical SOA reflects slower processing of visual information. Several studies using the backwards masking paradigm have shown that disabled readers have longer critical SOAs than age-matched controls (Di Lollo et al., 1983; Lovegrove & Brown, 1986; Mazer, McIntyre, Murray, Till & Blackwell, 1983; O'Neill & Stanley, 1976; Stanley & Hall, 1973). Therefore, in addition to having longer visible persistence than age-matched controls, disabled readers appear to process visual information more slowly.

However, not all studies using temporal integration and backwards masking paradigms have revealed differences between normal and disabled readers. A number of classic studies have failed to find impaired visual processing deficits in disabled readers (*e.g.*, Arnett & Di Lollo, 1979; Fisher & Frankfurter, 1977; Morrison, Giordani & Nagy, 1977). Although Kruk (Kruk, 1991; Kruk & Willows, 1993) demonstrated that dyslexic children were less accurate than normal readers on a backwards masking paradigm, there was no evidence of a reader group by SOA interaction. The lack of an interaction contradicts a key prediction of the temporal processing deficit hypothesis: that disabled readers' performance would be impaired *vis-à-vis* normal readers by short SOAs but not by long SOAs. Similarly, Farmer and Klein (1993) recently found that dyslexics did not have larger separation thresholds than either chronological-age matched or reading-level matched children in a temporal integration task. Rayner and his colleagues aptly summarize the position of critics of visual processing deficits in their conclusion (Rayner et al., 1995) "While there are undoubtedly some dyslexics who have visual problems, most of the research on dyslexia suggests that problems with reading caused by the visual mechanisms ... are quite rare (p. 506)."

In sum, review of the literature reveals that there is a lack of consensus regarding the role (and existence) of visual temporal processing deficits in developmental dyslexia. While a number of researchers convincingly argue that temporal visual processing may be the cause of some types of developmental dyslexia (e.g., Lovegrove et al., 1986; Willows, 1991), others argue equally convincingly that such a hypothesis is implausible (e.g., Hulme, 1988). This thesis will attempt to at least partially resolve some of the controversies surrounding this issue.

Evidence Regarding Domain-General Temporal Processing Deficits in Developmental Dyslexia

Language Production and Motor Control

Proponents of the first two variations of the timing hypothesis argue that temporal processing deficits are limited to perception. However, proponents of a domain-general temporal processing deficit have argued that the difficulties experienced by disabled readers are not restricted to the perception of rapidly presented sequences of stimuli. This stems from the observation that dyslexics experience difficulties in language production. For example, Catts (1991) reported that poor readers have a variety of problems pronouncing a variety of linguistic material. These problems are apparent in the production of familiar but phonologically complex words and phrases, such as "cinnamon" and "seashells", the acquisition of new words (especially multisyllabic words), and the production of complex phonological sequences (Gathercole & Baddley, 1987; Taylor, Lean & Schwartz, 1989). Wolff, Michel, an Ovrut (1990b) compared the ability of dyslexics to repeat syllables at prescribed rates to the performance of normal readers and learning disabled adolescents without dyslexia. Dyslexics deviated from the prescribed rate more than the comparison groups, always repeated syllables too slowly, and made more sequencing errors than either comparison group. While the performance of all groups deteriorated as the prescribed rate increased, dyslexics were penalized by the fastest rates to a much greater extent than the normal readers and learning disabled subjects. Therefore, dyslexics' ability to sequence verbal stimuli appears to be very sensitive to temporal constraints.

It is important to note that the verbal deficits reported by Wolff et al. (1990) were greatest at the fastest speeds. Rate variables also play an important role in dyslexics' deficits in automatized naming tasks (Wolff, Michel & Ovrut, 1990a). The Rapid Automatized Naming (RAN) paradigm has been used to provide strong evidence for processing speed deficits in dyslexia (Denckla, 1972; Denckla & Rudel, 1976; Wolf, 1991a, 1991b). In this paradigm, subjects are given a card containing several rows and columns of stimuli which they must name as quickly and accurately as possible. A variety of studies have found that dyslexics name pictures, colours, letters and digits more slowly than normal readers (Ackerman, Dykman & Gardner, 1990; Bowers & Swanson, 1991; Bowers & Wolf, 1993; Katz, Curtiss & Tallal, 1992; Torgesen, Wagner, Simmons & Laughon, 1990; Wolf, 1991a, 1991b; Wolff et al., 1990a). Even when the RAN task is simplified by presenting stimuli individually, dyslexics still show speed deficits (Bowers & Swanson, 1991; Fawcett & Nicolson, 1994; Wolff et al., 1990). Bowers and Swanson's (1991) investigation of dyslexics' speed deficit in retrieving names was assessed using both the continuous list and discrete-trial methodologies, with discrete trials presented at slow and rapid rates. Although dyslexics named digits more slowly than average readers in all conditions, the group differences are larger on the continuous list format. On the discrete-trials of the RAN, reader group interacted with presentation speed, such that poor readers were especially penalized at rapid rates. This replicates Wolff et al.'s (1990a) finding that dyslexics showed no naming impairments when stimuli were presented slowly, but were heavily penalized by rapid presentation. If naming speed reflects the precise timing mechanism necessary to integrate phonological codes (Bowers & Wolf, 1993), dyslexics' impaired performance at rapid speeds may be caused by deficits in their timing mechanisms.

One might argue that slow performance on the RAN task reflects language problems, such as impeded word retrieval, rather than a deficient timing mechanism. However, work by Katz and his colleagues (Katz et. al., 1992) suggests that impaired RAN performance may result from an impaired timing mechanism. In their study, the standard, oral version of the RAN was paired with a manual version. In the manual version of the RAN, language impaired and normal children pantomimed the functional use of five objects instead of naming them. These objects were HAMMER, TOOTHBRUSH, COMB, FORK, and BALL. Language impaired children performed more poorly than controls on both versions of the RAN. An important finding was that performance on the oral and manual versions of the RAN were significantly correlated for language impaired children, but performance on the two tasks was unrelated for normal children.

Katz suggests that these data show that the language impaired children's RAN deficits reflect a domain-general impairment in processing rapid sequential stimuli.

However, while Katz et al.'s (1992) study may be suggestive of a common timing mechanism involved in rapid naming and motor sequencing abilities, one might also argue that performance on the manual version of the RAN is linguistically mediated. One reason for the correlation between manual and oral versions of the RAN for language-impaired children may be that these children have difficulties retrieving the names and the functional uses of the objects. Retrieval of the objects' names and functional uses may be the rate-limiting factor in the task. If retrieval of an object's name or use is the rate limiting factor. than performance on the two tasks would be correlated. In the case of normal children, word retrieval (or the retrieval of semantically related items, such as the functional uses of objects) is no longer a rate-limiting factor in the two tasks, so performance on the tasks are uncorrelated. Therefore, while the impaired performance of language-impaired children on both manual and oral versions of the RAN may reflect a domain-general temporal processing deficit, a viable alternative hypothesis is that it may be linguistically mediated.

There is an additional reason why Katz and his colleagues' (1992) results must be interpreted with caution. Although dyslexia may be conceptualized as a milder form of a language disability (Catts, 1991; Scarborough, 1990; Stanovich & Siegel, 1994), one cannot be sure that their findings can be generalized to individuals with reading disabilities but who are not language-impaired. However, work by Wolff and his colleagues suggest that dyslexics do have deficits in the rate and timing precision in bimanual coordination (Badian & Wolff, 1977; Klicpera, Wolff & Drake, 1981; Wolff, Michel, Ovrut & Drake, 1990c). Badian and Wolff (1977) found that reading-disabled boys could coordinate tapping a single finger in beat with a metronome as well as younger average readers. However, when they were asked to alternate hands, dyslexic boys' tapping deteriorated and was worse than the younger boys. Similarly, Klicpera et al. (1981) found that dyslexic adolescents tapped as well as normal readers when they either used one hand, or both hands in unison. However, when they alternated hands, their performance deteriorated much more than the normal readers. Finally, Wolff et al. (1990c) explored how the rate of the metronome might influence performance. While dyslexic adults and adolescents could tap in alternation as well as normal readers when the metronome was set at slow rates, dyslexics' performance was impaired at fast rates. It is important to note that this impairment is unique to dyslexia and not learning disability in general. Learning disabled adolescents who were not dyslexic tapped as well as normal subjects, even at the rapid rates. Therefore, impaired tapping skill is unique to developmental dyslexia, and not learning disabilities in general.

In sum, several studies have suggested that disabled readers have impaired performance on perceptual, language production and motor tasks which require rapid processing. These findings provide a rationale for the further investigation of temporal processing deficits in developmental dyslexia. Nevertheless, these studies are not without their critics.

Limitations in the Literature on Timing Deficits

Although several studies have suggested that temporal processing deficits underlie developmental dyslexia, there are some serious problems in the literature. The first problem--the Achilles' heel of the theory--is as follows. The majority of the research studies attempt to link temporal processing deficits with reading disabilities. In fact, many propose that the temporal processing deficit underlies the phonemic deficit characteristic of dyslexia (e.g., Farmer & Klein, 1995; Tallal, 1980). However, with the exception of Bowers and Swanson (1991), few can link temporal processing deficits with the phonological core processes because they have examined few, if any, phonological measures. Although Tallal (1980) found a significant Spearman Rank correlation between performance on her TOJ task and pseudoword reading, Bowers and Swanson failed to find significant correlations between measures of digit naming speed and measures of phonological processing and phonological awareness. However, naming speed did contribute unique variance to word recognition, independent of measures of phonological awareness. Although Bowers and Swanson's findings present an important link between naming speed and reading skill which supports the temporal processing deficit hypothesis, it has also been argued that naming speed is a measure of phonological processing. In fact, Wagner and Torgesen (1987) have argued that the RAN paradigm assesses phonological recoding in lexical access, or name retrieval. If slow naming rates reflect phonological deficits but not temporal processing deficits, than there is no evidence providing causal links between timing deficits and reading failure. In short, the three variations of the timing hypothesis assume that impaired temporal processing is the cause of the phonological processing deficits without directly testing these causal links. The purpose of this thesis is to directly examine the relationship between temporal processing, phonological processing and reading skill.

A second serious problem in the literature lies in the selection of dyslexic subjects. The criteria for the classification of dyslexia is often based on performance at least one to two years behind grade level on a reading comprehension test, which generally is discrepant with IQ scores (*e.g.*, Fawcett & Nicolson, 1994; Wolff et al., 1990a, 1990b; Zurif & Carson, 1970). This criterion for subject selection is problematic. First, the use of a reading comprehension test is questionable (see Siegel & Heaven, 1986). Poor performance on reading comprehension tasks may result from poor memory, attentional difficulties, and language impairments, in addition to deficient decoding skills.

Another problem in subject selection lies in the use of a discrepancy of reading level from IQ as a means of classifying dyslexics. A growing body of research has shown that the degree of aptitude-achievement discrepancy is unrelated to word recognition performance of children with RD (Das, Mishra & Kirby, 1994; Felton & Wood, 1992; Fletcher, Francis, Rourke, Shawitz & Shaywitz, 1992; Fletcher, Shaywitz, Shankweiler, Katz, Liberman, Stuebing, Francis, Fowler & Shaywitz, 1994; Shaywitz, Fletcher, Holahan & Shaywitz, 1992; Siegel, 1988, 1989, 1992; Stanovich, 1991; Stanovich & Siegel, 1994). For example, Felton and Wood demonstrated that reading-disabled children with low IQ scores do not differ from those with higher IQ scores in a variety of tasks that were related to reading. These tasks included pseudoword reading, the decoding of single words, and passage comprehension. Similarly, indicators of poor reading, such as weak phonological sensitivity, is uncorrelated with IQ scores (Fletcher et al., 1992). Thus, the literature provides strong evidence that aptitude-achievement discrepancies are irrelevant to the definition of dyslexia. Therefore, when researchers remove dyslexic subjects whose reading scores are not discrepant from their IQ scores from their samples, they may have altered the nature of their sample. Thus, this thesis will attempt to avoid these problems by using the objective measure of WRAT3 reading scores below the 26th percentile as the criterion for dyslexia.

Finally, a related problem lies in the selection of controls. Most of the studies failed to include as controls reading level matched children. The use of reading-level controls is important in understanding the nature of reading disabilities (Bradley & Bryant, 1983; Bryant & Impey, 1986; Felton & Wood, 1992; Olson et al., 1989; Stanovich & Siegel, 1994; Stanovich et al., in press). By comparing the older, disabled readers to younger, normal readers, one can tease apart whether the reading disability results from the slower development of cognitive skills, or if the reading disability reflects a developmental deficit. If disabled readers' performance differs from that of the reading-level controls, one may infer that their performance is the result of a true, selective deficit (Felton & Wood, 1992). However, if less-skilled readers' performance matches that of the reading level match, their performance may by explained by the slower maturation of reading. Therefore, the failure to include reading-level controls has been a serious problem. While authors, such as Tallal, have argued that an auditory temporal processing deficit underlies the phonological core deficit of developmental dyslexia, the absence of reading-level controls has prevented the precise evaluation of the specificity of the deficit hypothesized.

Summary of the Rationale for the Present Study

Although the temporal processing deficit hypothesis has attracted growing attention as a causal explanation for reading failure, the body of evidence supporting it has some serious limitations. Of particular importance is the absence of empirical support for the basic assumption that impaired temporal processing is the underlying cause of the phonological deficit that characterizes developmental dyslexia. Therefore, in its investigation of the temporal processing deficit hypothesis of developmental dyslexia, the current thesis directly tested the causal links between temporal processing, phonological awareness and reading failure. This investigation will adopt a multivariate approach, in which variables relevant to the phonolgical core deficit will be included along with a variety of timing tasks in various domains. The multivariate approach enables the use of several statistical procedures, such as regression and commonality analyses, which clarify the relationship between the timing variables, phonological processing and reading skill. The use of several statistical procedures enables one to determine if group differences on the timing tasks are meaningful as a causal explanation for reading failure. Finally, the use of younger, skilled readers as a reading-level match would shed light on the specificity of the hypothesized timing deficit. Thus, the goal of this thesis is the critical examination of temporal processing deficit hypothesis of developmental dyslexia. To achieve this goal, the following research questions were addressed.

1) Do disabled readers suffer from impaired temporal processing? If so, what is the nature of this deficit (i.e., is it restricted to auditory and/or visual modalities, or is it a domain-general deficit that affects perceptual, verbal and motor capacities)? If so, would impaired temporal processing best be described using a maturational-lag or a deficit model?

2) What is the relationship between temporal processing and phonological processing?

METHOD

Participants

Thirty adults were classified as disabled readers (RD; 17 female and 13 male) based on their performance (reading at or below the 25th percentile) on the reading subtest of the Wide Range Achievement Test - 3 (WRAT-3; Tan Form; Wilkinson, 1995). Thirty-two adults who were reading above the 29th percentile on the WRAT-3 served as chronological-age controls (CAC; 16 female and 16 male). Thirty-one children who were normal readers, reading at or above the 30th percentile on the WRAT-3 reading subtest, served as reading-level controls (RLC; 19 female and 12 male). All participants were native English. The mean age for the adults classified as disabled readers was 25.23 years (SD 5.96 years), and for CAC adults was 25.43 years (SD 7.4 years). The mean age for children was 9.73 years (SD 1.57 years). The psychoeducational profiles of each group are presented in Table 1.

Most participants were referred to this study by parents, schools, or social agencies. Many of the 16 CAC participants who had been referred to the study have experienced difficulties in school or wished to return to school after a prolonged absence. The participation of 16 CAC and 21 RLC subjects was recruited through advertisements seeking skilled readers. Adults who had been recruited through advertisements were paid $40.00 for their participation, while children who were recruited through advertisements were paid $20.00.

Procedure

All participants were tested individually in a single session. The entire battery was administered to adults, and lasted approximately 5 hours. However, due to fatigue and the length of the entire battery, only a subset of the experimental tasks were administered to children. The testing session for children included at least one task from each domain of the timing tasks. The shortened battery for children involved approximately 3 hours of testing. After participants had given informed consent, a battery of standardized reading and intelligence measures, phonological tasks, and "timing" tasks were administered. The timing tasks were designed to tap perceptual, manual and oral motor proficiency.

Table 1.

Participant Characteristics

	Dyslexic Adults (n=30)		CAC Adults (n=32)		RLC Children (n=31)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Age (years)	25.23^{a}	5.96	25.43^{ba}	7.40	9.73^{b}	1.57
Estimated full scale IQ	86.83^{a}	11.75	108.45^{b}	12.40	108.87^{b}	17.91
WRAT3 Reading						
Raw Score	35.97^{a}	4.29	49.50^{b}	3.66	37.74^{a}	7.02
Percentile	8.33^{a}	8.46	66.44^{b}	18.41	67.97^{b}	20.78
WRAT3 Spelling						
Raw Score	30.63^{a}	5.61	44.44^{b}	4.35	31.00^{a}	6.10
Percentile	9.8^{a}	11.82	66.28^{b}	22.20	56.67^{a}	25.63
WRAT3 Arithmetic						
Raw Score	34.83^{a}	4.44	43.22^{b}	4.21	30.55^{c}	5.28
Percentile	17.53^{a}	17.54	59.50^{b}	25.60	58.40^{b}	21.45
WIAT Listening Comprehension						
Raw Score	25.48^{a}	3.67	33.61^{b}	11.76	24.85^{a}	5.19
Percentile	32.24^{a}	22.49	72.42^{b}	27.25	72.42^{b}	26.96

Note: Means with different superscripts differ significantly.

Standardized Measures. In addition to the reading subtest of the WRAT-3 (Tan form), all participants were administered the spelling and arithmetic subtests of the WRAT-3 (Tan form). Form G of the Word Identification subtest of the Woodcock Reading Mastery Tests (Woodcock, 1987) served as a second measure of word recognition ability, while the Word Attack subtest of the Woodcock Reading Mastery Tests (Form G) was administered as a test of pseudoword reading. Oral comprehension was assessed using the listening comprehension subtest of the Wechsler Individual Achievement Test (WIAT; Wechsler, 1992). Adults' reading comprehension was assessed using the Nelson Denny Reading Comprehension Test (Brown, Nelson & Denny, 1973), while the Stanford Diagnostic Reading Test (Form G; Karlsen & Gardner, 1985) measured children's reading comprehension. Finally, the vocabulary, block design, digit span and digit symbol subtests of the Wechsler Adult Intelligence Scale - Revised (WAIS-R; Wechsler, 1981) were administered to all participants aged 16 years and older. Younger participants received the vocabulary, block design, digit span and coding subtests of the Weschler Intelligence Scale for Children (WISC; Wechsler, 1974).

Phonological Sensitivity. Two tasks were used to assess phonological sensitivity. First, Rosner's Auditory Analysis Test (Rosner & Simon, 1971) was administered. This task requires participants to delete phonemes and syllables from words. In this task, the experimenter asked the participant to repeat a word, such as "cowboy". After the participant repeated the word correctly, the experimenter asked what sounds would remain if a part of the word, such as "boy", was deleted (the astute reader would note that the correct response is "cow"). Participants were then given two additional practice items, in which they deleted "tooth" from "toothbrush" and /s/ from "sat". These practice items were followed by 40 test items arranged approximately in ascending difficulty, requiring participants to delete syllables from compound words, and single phonemes from the initial and final positions in words. They deleted single phonemes from blends in the initial or final position or internal to the blend. Participants were also asked to delete the medial syllables from the final items, some of which did not form real words. The maximum score on this task was 40, and the overall mean score was 27.60 with a standard deviation of 9.32. The split-half reliability of this task , as calculated by the Spearman-Brown corrected correlation, was .96.

Phonological Coding. This task was an adaptation of Olson, Kliegl, Davidson and Fotz's (1985) Phonological Choice Task, which taps phonological recoding skill without requiring the overt pronunciation of pseudowords. In this task, participants were presented 26 pairs of pseudowords, such as *kake-dake*, written on cards. One pseudoword in each pair was a pseudohomophone. That is, it sounded like a real word when pronounced. Participants pointed to the pseudoword they thought was a pseudohomophone. The number of pseudohomophones correctly identified was used as the dependent measure, with a maximum score of 26. Across the three groups, the mean of this task was 22.17 and the standard deviation was 4.03. The split-half reliability for this task (Spearman-Brown corrected correlation) was .85.

Orthographic Sensitivity. The Orthographic Choice Task (Siegel, Share & Geva, 1995; Stanovich & Siegel, 1994) tested participants' knowledge of spelling patterns in English by requiring them to make word-likeness judgments. In this task, participants were shown 17 pairs of pseudowords, such as *milg-miln*, written on cards. One pseudoword in each pair only contained orthographic patterns that occurred in English, while the other contained at least one orthographic pattern that did not occur in English. Participants pointed to the pseudoword that they thought was more word-like (*i.e.*, the one that did not contain any illegal spelling patterns). The number of word-like pseudowords correctly identified served as the dependent measure, and yielded a maximum score of 17. The overall mean score on this task was 14.16, with a standard deviation of 2.19. The Spearman-Brown corrected split-half reliability for this task, at .55, was unfortunately quite low.

Experimental Words. Participants were presented a set of 48 words taken largely from the set investigated by Coltheart and Leahy (1992). The experimental words varied along the dimensions of regularity and consistency (see Coltheart & Leahy, 1992; Glushko, 1979; Patterson &

Morton, 1985; Seidenberg, Waters, Barnes & Tannenhaus, 1984; Taraban & McClelland, 1987). Regularity refers to the degree of the predictability of the pronunciations of words based on the assumption that small-unit orthographic units (e.g. graphemes) are employed in the word recognition process. Consistency refers to the degree of predictability of the pronunciations of words based on the assumption that large-unit orthographic units (e.g. word bodies) are used in the word recognition process. These dimensions are orthogonal in theory. When the two are crossed, they yield the four categories from which 36 of the 48 words were drawn. The first category of regular-consistent words (e.g., stiff) contained vowels pronounced with their most frequent small-unit correspondence, based on a context-free count of grapheme-phoneme correspondences (see Berndt, Reggia & Mitchum, 1987), and had word bodies (e.g., _iff) with consistent pronunciations. Regular-inconsistent words (e.g., "paid") also contained vowels that were pronounced with their most frequent pronunciation, but had neighbours that shared the same word body and that were pronounced differently (e.g., "said" is a neighbour of "paid"). Irregular-consistent words (e.g., "walk") are those that have vowel pronunciations which are not the most common, but have many neighbours that share their word bodies and pronunciations (e.g., "walk" and "talk"). Finally, the category of irregular-inconsistent words (e.g., "pint" and "broad") included words with uncommon vowel pronunciations that have many neighbours whose word bodies are pronounced differently. The 12 remaining words were considered "unique" (Seidenberg et al., 1984; Waters & Seidenberg, 1985). These words have irregular pronunciations, and few orthographic neighbours (e.g., "yacht" and "aisle"). These categories were used to illustrate the variability of the stimuli along these dimensions. However, in this study, regularity and consistency were investigated as continuous variables, rather than as the discrete categories presented above.

A Classic II MacIntosh computer running Superlab 1.6.8 was used both to present stimuli and to record response latencies. Each word was presented in black Geneva 12 point font, centered on the white computer screen, for a maximum of 5000 ms. Participants attempted to read each word aloud. Voice onset terminated the presentation of each stimulus, and was followed by a 1000 ms interstimulus interval (ISI). The pronunciation of each word was recorded by the experimenter.

Response latencies were calculated by the computer as the interval between the stimulus onset and voice onset. Two types of errors were recorded. Words that were pronounced incorrectly were scored as errors. All responses with latencies under 200 ms were considered mistrials, while those with latencies over 1500 ms were scored as latency errors. Subjects whose response latencies were extreme were identified using an outlier analysis. Outliers' scores were changed according to the procedure described by Tabachnick & Fidell (1983, p.76). The outlying case's RT was assigned a latency one unit larger (one millisecond) than the next largest latency. This procedure preserves the deviancy of the outlier's score without allowing it to be so deviant that it excessively influences correlation and regression analyses.

Experimental Nonwords. Participants attempted to pronounce 30 experimental pseudowords. Fifteen of the pseudowords were drawn from the set compiled by Coltheart and Leahy (1992), while the remaining 15 were newly constructed. Like the experimental words, the pseudowords varied across the dimensions of regularity and consistency, representing three categories. One set of pseudowords had _VC word bodies that were derived from regular-consistent words (e.g. hile and fump). A second set of pseudowords were derived from bodies of irregular-consistent words (e.g. jook, and nalk). The final set of pseudowords, the ambiguous-inconsistent set, had word bodies derived from words that are pronounced in several ways, such as zave (which may rhyme with gave, have and suave) and yone (which may rhyme with done, gone, and phone). Once again, because regularity and consistency were investigated as continuous variables, these categories are used to illustrate the variability within this set of pseudowords.

A Classic II MacIntosh running Superlab 1.6.8 was used both to present stimuli and to record response latencies. Each pseudoword was presented in black Geneva 12 pt font, centered on the white computer screen for a maximum of 5000 ms. Participants attempted to read each pseudoword aloud. Voice onset terminated the presentation of each stimulus, and was followed by a 1000 ms interstimulus interval (ISI). The pronunciation of each word was recorded by the experimenter. Response latencies were calculated by the computer as the interval between the stimulus onset and voice onset. All responses with latencies under 200 ms were considered mistrials, while those with latencies over 1750 ms were scored as latency errors. Cases with extreme latencies were identified and adjusted using the procedure outlined for the experimental words.

The accuracy of pronunciations was coded according to both strict and lenient criteria. For the strict criterion, all vowels and consonants had to be pronounced in accordance with vowels and consonants in some real words with identical _VC word bodies. For example, the pronunciation of the pseudoword "zave" would have to rhyme with one of the real words gave, have, and suave. All other pronunciations were scored as incorrect using the strict criterion. For the lenient criterion, the pronunciation of the vowel had to conform with the pronunciation of that vowel in some real word with the same general vowel-consonant configuration, but not necessarily one with the identical word body. For example, the vowel in "voot" could be pronounced as the vowel in "blood" using the lenient criterion, but not according to the strict criterion.

Exposure to Print. The Magazine Recognition Test (MRT; Stanovich & Cunningham, 1992) was administered to adults as an index of relative differences in exposure to print. This checklist contained 60 titles of popular magazines, and 30 foils. Participants checked the titles that they thought were real magazines. The score of this task was calculated by subtracting the number of foils selected, divided by 0.3, from the number of real magazines selected, divided by 0.6. This formula yielded a maximum possible derived score of 100. All derived scores less than zero were assigned values of zero. The overall mean score on this task was 39.14, with a standard deviation of 21.56.

Timing Tasks

Rapid Automatized Naming (RAN). Participants named five monosyllabic digits (1, 2, 4, 6, and 8) in both sequential and serial variations of this task (*i.e.*, continuous and discrete variations of RAN). Participants first completed the sequential, or continuous, version of the RAN, which was based on the task used by Denckla and Rudel (1976). In this task, participants were presented a chart of 50 numbers presented in a matrix of 10 columns and 5 rows. The order of the digits was randomized, with each digit presented 10 times. Digits were printed using bold Technical 24 point font. Participants named the 50 digits from left to right, starting with the top row and ending on the bottom row. The total naming time was recorded by the experimenter using a stopwatch. Participants' responses were recorded with a tape recorder, so that uncorrected errors could be enumerated. Thus, the dependent variables of the sequential version of the RAN were: accuracy, total naming time and naming time per digit (total time in ms divided by 50).

The serial, or discrete, version of the RAN task was based on the methodology used by Bowers and Swanson (1991). The MacIntosh computer was used to present stimuli and record data. Participants completed one block of ten practice items and two blocks of fifty test trials. In each trial, a black digit presented in Geneva 12 pt font appeared in the centre of the screen. The five digits (1, 2, 4, 6 and 8), each repeated ten times within both blocks, were presented in semi-random order. Presentation of each stimulus was terminated by voice onset, and the latency of participants' responses was recorded by the computer. Response latencies were calculated as the interval between the stimulus onset and voice onset. In the block of ten practice items, the letters a through j were presented in alphabetical order, with the subsequent letter appearing 1250 ms after the presentation of the previous letter had terminated. In the first block of trials, the subsequent digit appeared 1250 ms after the presentation of the previous stimulus had terminated. This was known as the *slow* condition. In the second block of trials, the interval between voice onset and the presentation of the subsequent stimulus was 250 ms. This was the *fast* condition. Because the goal of this thesis is to examine individual differences, the order of the blocks was not counterbalanced. The slow block was presented first so that confusions while learning the task would be minimized. All latencies under 200 ms were counted as mistrials, while latencies greater than 1750 ms were scored as latency errors. Cases with extreme latencies were identified and adjusted using the procedure outlined for the experimental words.

Diadochokinesis (DDK). The syllable repetition task that was used to examine the temporal organization of oral movement at different rates was adapted from the work of Wolff, Michel and

Ovrut (1990b). A MacIntosh computer was used to present stimuli and responses were saved using a tape recorder.

In this task, participants repeated three sets of syllables in time to the beat of a metronome. The sets included two pairs of syllables, "pa-ta" and "ta-ka", and one set of three syllables, "pa-ta-ka". Once a trial began, the computer emitted a 1000 Hz tone for ms at regular intervals. Participants immediately attempted to synchronize their repetition of the syllables with the tones. The first syllable of each set was synchronized with the beat of the metronome, while the set's subsequent syllables were uttered in between beats. Thus, when participants repeated "pa-ta-ka", the "pa" was uttered with the tone, while "ta-ka" was uttered in the interval between tones. Participants were required to repeat the pairs of syllables at least fifteen times and pa-ta-ka a minimum of ten times without stopping. If a participant stopped in the middle of a trial, that trial was repeated at the end of the task.

Participants repeated each set of syllables at the two rates employed by Wolff et al. (1990b). Thus, there were six sets of trials in this task. For the slow rate, the computer "beeped" every 556 ms for two-syllable sets and 833 for the three-syllable string. Thus the slow speech rate required participants to utter a syllable every 278 ms. For the fast rate, the computer emitted a tone every 326 ms for the two-syllable sets and every 462 ms for the three-syllable set. Therefore, participants uttered a syllable every 163 ms in the rapid trials.

Three measures were obtained for each trial and at each speed: a) *Speech Sequencing Errors* included deletions, incorrect repetitions, reversals (e.g., "ta-pa" instead of "pa-ta") and intrusions (e.g., "ta" replaced with "ga"). A maximum of one error was scored for any string of three syllables. b) *Time Coherence* referred to the success with which participants synchronized the first syllable with the tones. The standard deviation of the intervals between the utterance of the first syllable of each sequence quantified participants' temporal coherence. c) *Speech Rate* reflected participants' success at repeating the syllable sequences at the prescribed rates. The mean interval between the utterance of the first syllable of each sequence was used as the speech rate.

After completing the syllable repetition task, a maximum repetition rate was obtained. Four repetition rates were obtained, one for each of the syllables pa, ta, and ka, and the sequence pa-ta-ka.

When the experimenter told them to begin, participants repeated each of these as rapidly as possible. After five seconds, the experimenter told the participant to stop. The number of repetitions for each 5 second trial was used as the maximum repetition rate.

Gap Detection. Many authors have used gap detection tasks to determine the minimum interstimulus interval (ISI) necessary for a person to perceive that a stimulus has been interrupted by a temporal gap (see Farmer & Klein, 1995 for a review). Gap detection requires one to perceive the presence of a stimulus, followed by its absence and subsequent reappearance. Because performance may vary across sensory modalities, the gap detection task was administered both visually and auditorily.

Visual Gap Detection. The visual gap detection task was based on the paradigm used by Lovegrove and his colleagues (Badcock & Lovegrove, 1981; Lovegrove, Heddle & Slaghuis, 1980; Lovegrove, Slaghuis, Bowling, Nelson & Geeves, 1986). In this task, participants decided whether the presented stimulus flickered on the computer monitor.

A MacIntosh computer running Superlab 1.6.8 was used to both present stimuli and collect responses. The screen's brightness was dimmed to the lowest setting to make discrimination more difficult . There were 160 trials in this task. For 80 trials, a line grating was presented in the centre of the computer screen for 170 ms. These were the "no flicker trials". In the 80 "flicker" trials, two identical line gratings were presented successively, each one for 75 ms. These gratings were separated by intervals of 0, 20, 40, 60, 80, 100, 140, and 180 ms. 16 ms were required to "write" the screen. Therefore, with the additional time required to write the screen, the eight ISIs were 16, 36, 56, 76, 96, 116, 156, and 196 ms. Ten trials were presented using each of these ISIs. The order in which these trials were presented was randomized for each participant.

Each trial began with the presentation of a black asterisk in the centre of the screen for 500 ms. The screen was blank for a 500 ms interval. Then, the line grating(s) were presented. The screen was blank until the participant had made a response. Once a response had been made, the next trial began. Participants were instructed to press "b" key, which was marked with a blue sticker if the stimulus flickered, or flashed on the screen twice. Participants were also instructed to press the "n" key, which was labeled with a red sticker, if the stimulus only flashed once. All responses were made using the index finger of the dominant hand. Responses under 200 ms were scored as mistrials, and responses longer than 1750 ms were scored as latency errors. Cases with extreme scores were identified and adjusted using the procedure outlined for the experimental words. As a measure of reliability, the median Spearman-Brown corrected correlation between response latencies in the flicker condition was used, which was .97.

Auditory Gap Detection. This task was the auditory analogue of the visual gap detection task. In this task, participants decided whether they heard one tone or two tones presented in rapid succession.

A MacIntosh computer running Superlab 1.6.8 was used to both present stimuli and collect responses. There were 160 trials in this task. For 80 trials, a 1000 Hz tone was presented over headphones for 170 ms. These were analogous to the "no flicker trials" in the visual gap detection task. In the 80 trials that contained a gap, two 1000 Hz tones were presented successively, for 75 ms each. The two tones were separated by intervals of silence. These intervals were 5, 10, 15, 20, 25, 35, 45, and 60 ms. For each ISI, ten trials were presented. A different random order was used to present these trials to each participant.

Each trial began with the presentation of a black asterisk in the centre of the screen for 500 ms. Then, the screen was blank. After a 500 ms interval, the tone(s) were presented. Participants responded whether they heard one tone or two. Once a response had been made, the next trial began. Participants indicated that they heard one tone by pressing the "n" key, which was marked with a red sticker, and two tones by pressing the "b" key, which was marked with a blue sticker. All responses were made using the index finger of the dominant hand. All responses under 200 ms were scored as mistrials and those longer than 2250 ms were scored as latency errors. Cases with extreme scores were identified and adjusted using the procedure outlined for the experimental words. As a measure of reliability, the median Spearman-Brown corrected correlation between response latencies in the flicker condition was used, which was .95.

Due to the design of both the visual and auditory gap detection tasks, the establishment of perceptual thresholds was untenable. However, the use of thresholds as measures of perceptual sensitivity is problematic in itself, particularly in its assumption that the response threshold is an index of the individual's sensitivity independent of other factors (Corso, 1963). However, response thresholds may be influenced by a variety of factors, both internal and external to the observer. In fact, Thompson (1920) argued that the threshold varies "at the subject's whim; and will vary with his mood at the moment (p.307)." Therefore, a metric which is able to separate the observer's sensitivity from response bias was used in the analyses. It is signal detection theory that provides this pure measure of sensitivity, d-prime (Tanner and Swets, 1954). D-prime, which is considered the most important sensitivity measure in signal detection theory, is generally calculated as the Z value of the hit-rate minus the Z value of the false alarm rate (MacMillan & Creelman, 1991). In the visual gap detection task, the percentage of incorrect responses in the no-gap (single stimulus) condition was used as the false alarm rate. Three hit rates were used to reflect accuracy when the ISI was short. The hit rate for the short ISI was the mean percentage of correct responses for ISIs of 0 and 20 ms. The medium hit rate was the mean percent correct responses for ISIs of 40, 60 and 80 ms, and the long hit rate was the mean percent correct responses for ISIs of 100, 120 and 140 ms. Thus, three d′s were calculated for the visual gap detection task. Similar measures were used for auditory gap detection. The false alarm rate was the percent incorrect responses in the no-gap (single stimulus) condition. The short hit rate was the mean percent correct responses for ISIs of 5 and 10 ms. The medium hit rate the mean percent correct for ISIs of 15, 20 and 25 ms, and the long hit rate was the mean percent correct responses for ISIs of 35, 45 and 60 ms. Thus, three d′s were also calculated for the auditory gap detection. To avoid the problem of infinite d-primes which occur when the hit or false alarm rates are either 100% or 0%, hit and false alarm rates were adjusted by adding .5 to the number correct and dividing this number by the total number of trials plus 1. This manipulation has little effect on the proportions and relative rankings of d-prime scores (Thorpe, Trehub, Morrongiello & Bull, 1988; Trainor & Trehub, 1993).

Seashore Rhythm Test. This subtest from the Halstead-Reitan Neurological Assessment Battery (Halstead, 1947) assessed participants' ability to discriminate auditory rhythmic patterns. This 30-item test requires participants to decide if pairs of rhythms are the same or different. The three sets of 10 items were arranged in increasing levels of difficulty. The rhythms of the first set contained 7 beats, the second set consisted of 9-beat rhythms, and the final set included 11-beat items. Participants were given three practice trials to familiarize them with the task. All items were presented by tape recorder. Across groups, the mean accuracy on this task was 26.20 with a standard deviation of 2.72. The maximum score on this task was 30, and the Spearman-Brown corrected split-half reliability of this task was .71.

Tapping Task. The tapping task was used to assess participants' ability to maintain a rhythm in the absence of feedback. In this task, participants tapped their index fingers in alternation. The keys that participants were instructed to press, the "X" and the "," keys, were marked with green stickers. Participants first attempted to synchronize their tapping with a 1000 Hz tone that was emitted for 75 ms by the computer at regular intervals. Thus, for each tone, participants pressed a green key. After providing the rate for 30 s, the computer ceased to provide feedback. Participants attempted to maintain the rhythm and rate of their tapping for an additional 60 responses.

This task was presented at two rates: fast and slow. In the fast rate, participants were required to make a response every 333 ms. In the slow rate, participants attempted to respond every 667 ms.

Three dependent measures were obtained for this task: a) *Tapping variability* reflected participants' ability to maintain consistent intervals between taps. Tapping variability was calculated separately for the left and right hands for both rates. The standard deviation of the interresponse intervals (IRI) quantified the consistency of intervals between taps. b) *Tapping errors* referred to the number of very early and very late taps. Once again, tapping errors were calculated separately for both hands. IRIs within a trial that exceeded the mean IRI for that trial by two or more standard deviations were considered tapping errors. c) *Tapping Rate* reflected participants' success at tapping at the prescribed rate. The mean IRI for each response was used as the tapping rate. Thus, the expected tapping rate for the slow trial was 750 ms, and 375 ms for the fast trial.

Drawing Lines and Crosses. An adaptation of the Bruininks (1978) task was administered to subjects. In this task, participants were given a ruled form with a vertical line through the centre of the page. First, participants drew crosses with the preferred hand for 15 seconds. All crosses were drawn from left to right along the horizontal rulings on the side of the centre line that corresponded to the preferred hand. Therefore, participants who were right-handed drew crosses to the right of the centre line, while left-handed participants drew crosses to the left of the centre line. Next, participants were given 15 seconds to draw vertical lines with the nonpreferred hand. Vertical lines were drawn from left to right between the horizontal rulings on the opposite side of the page. Finally, participants simultaneously drew crosses with their preferred hands and vertical lines with their nonpreferred hands for 15 seconds. Three scores were obtained for this task: the number of crosses drawn by the preferred hand, the number of lines drawn by the nonpreferred hand, and the number of lines and crosses drawn simultaneously.

Placing Pennies in a Box. The Placing Pennies in a Box subtest from Bruininks' (1978) battery was adapted. A corrugated plastic mat was placed on the table. A topless box with a 7 cm X 7 cm base with a height of 5 cm was placed in the centre of the mat. 25 pennies were placed flat on the mat, on the side of the box that corresponded to the participant's dominant hand. Thus, all coins were to the right of the box for right-handed participants.

Using their preferred hands, participants were given 15 seconds to place pennies, one by one, into the box. After recording the number of coins placed in the box, the experimenter lay all coins on the other side of the box. Thus, the pennies became easily accessible to participants' nonpreferred hands. Participants were then given another 15 seconds to place pennies, one after the other, into the box using their nonpreferred hands.

After each hand was tested individually, a second 7 cm X 7 cm X 5 cm box was placed on the mat next to the first one. An additional 25 pennies were added to the mat. The coins were arranged so that 25 coins lay flat on each side of the mat. Participants were given a final 15 seconds to pick up pennies and place them in the boxes. Although they were not required to simultaneously pick up coins with both hands, they were to place them in the boxes simultaneously. Three scores were obtained for this task: the number of coins placed in boxes by each hand independently, and the number of times the participant placed coins in the two boxes simultaneously. For each of these scores, the participants' fingertips must have extended beneath the rim of the box in order for the coin to be considered placed.

Finger Localization. Finally, Benton's (1955) finger localization task was administered. This task has been found to be predictive of later reading disability (Share et al., 1984). In this task, participants were required to identify the finger that had been touched under several conditions. First, participants were asked to lay their dominant hands on the table with the palms facing the ceiling and close their eyes. They were told that once their eyes were closed, one of their fingertips would be touched with the cap of a pen. Once the finger had been touched, participants were required to point to the finger that had been touched with the opposite hand. After all five fingers of the dominant hand had been touched, the procedure was repeated on the nondominant hand. Thus, five trials were completed on each hand, yielding a maximum score of 10 on this subtest.

After completing this procedure on both hands, a full-scale outline of a hand that matched the orientation of the dominant hand was placed on the table. Participants were told that the task would be repeated, but instead of indicating which finger had been touched by pointing to it, they would point to the corresponding finger on the map. After stimulating each finger of the dominant hand, the procedure was repeated on the nondominant hand, using a map that matched the nondominant hand in orientation. Once again, five trials were completed on each hand using this procedure. The maximum score of this subtest was 10.

Finally, participants were instructed to put their hands on the table, facing upwards. This time, two fingers were touched simultaneously. Participants then indicated which fingers had been stimulated, either by pointing to the chart or to the fingers themselves. Five trials were completed on each hand. The maximum score of this subtest was 10. The three subtests were totalled to yield a maximum score of 30 for the finger localization task. Across groups, the mean accuracy on this task was 27.97 with a standard deviation of 1.90. The Spearman-Brown corrected split-half reliability of this task was .69.

Results

Group Comparisons

A series of ANOVAs comparing the performance of the reading-disabled adults to the performance of CAC adults and RLC children on the standardized and experimental reading measures was conducted. Table 2 presents the groups' means on several of the word recognition and reading comprehension measures. Recall that adults had been classified as RD or chronological-age controls (CAC) based on their performance on the reading subtest of the WRAT3, and the reading-level controls had been selected so that their mean raw score on the reading subtest of the WRAT3 would match the mean of the older disabled readers. This method of group matching yielded a pattern of performance in which the three groups' WRAT3 reading raw scores differed significantly, $F(2,90) = 62.98$, $p<.001$, with Scheffe post-hoc tests revealing that RD adults read significantly fewer words than CAC adults, but not RLC children. This pattern of results was replicated using both the standardized and experimental word reading tasks. The three groups differed significantly on the Woodcock Word Identification, $F(2,90) = 44.17$, $p<.001$, and the Coltheart Word Reading Task, both in accuracy, $F(2,77) = 26.24$, $p<.001$, and latency, $F(2,72) = 21.975$, $p<.001$. On each word reading measure, RD adults performed more poorly than CAC adults, but did not differ significantly from the RLC children. The RD adults also performed more poorly than CAC adults on the reading comprehension measure, the Nelson-Denny Reading Comprehension Test, $t(58) = 7.87$, $p < .001$.

Table 3 displays the results of a series of ANOVAs conducted to compare the performance of the three groups on the standardized and experimental measures testing phonological processing. The results from this sample of RD adults were convergent with those from the majority of other samples in the literature by displaying a significant deficit in pseudoword reading on the Woodcock Word Attack measure *vis-à-vis* CAC and RLC children (Gottardo et al., in press; Rack et al., 1992; Siegel & Ryan, 1984; Stanovich & Siegel, 1994).

Table 2: Group Comparisons on Standardized and Experimental Reading Measures

	RD Adults (n=30)		CAC Adults (n=32)		RLC Children (n=31)	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
Standardized Measures						
Woodcock Word Identification						
Raw Score	75.20^{a}	9.15	97.41^{b}	5.39	73.68^{a}	16.33
Nelson-Denny Reading Comprehension						
Raw Score	22.82^{a}	9.82	48.86^{b}	14.90		
Experimental Measures						
Coltheart Words						
Accuracy	0.66^{a}	0.21	0.93^{b}	0.07	0.75^{a}	0.12
Latency (ms)	946.40^{a}	215.83	671.28b	116.36	871.10^{a}	129.62

Note: Means with different superscripts differ significantly.

That is, the raw scores of the three groups differed significantly, F(2,90) = 30.00, p<.001, and the RD adults read significantly fewer pseudowords than both CAC adults and the RLC children. These results converge with the results obtained from the experimental pseudowords. The three groups' skill at reading experimental pseudowords differed significantly, regardless of whether the strict scoring system, F(2,86) = 35.92, p<.001, or lenient scoring system, F(2,86) = 33.70, p<.001, had been used. For each measure of accuracy for pseudoword reading, Scheffe post-hoc tests revealed that the CAC adults performed significantly better than RLC children, who performed significantly better than RD adults. Although the speed with which the groups accurately read experimental pseudowords differed significantly, whether the strict, F(2,73) = 8.83, p<.001, or lenient, F(2,73) = 6.21, p<.005, scoring systems had been adopted, the only difference revealed by Scheffe post-hoc tests was that RD adults were significantly slower than CAC adults. The phonological processing deficit displayed by RD adults is indicated by performance significantly worse than both the CAC and RLC groups on the Rosner Auditory Analysis Test, F(2,90) = 20.856, p<.001, and the Phonological Choice Task, F(2,89) = 20.063, p<.001. Although the Phonological Choice Task tends to be insensitive due to its design (*i.e.*, 26 pairs of forced-choice items), and was unable to detect differences between CAC adults and RLC children, it successfully discriminated between the RD adults and RLC children. In summary, these results indicate that the phenotypic performance profile of this group of disabled readers mirrors that of most other groups reported in the literature (Stanovich & Siegel, 1994).

Table 3: <u>Group Comparisons on Standardized and Experimental Measures Testing Phonological Processing</u>

	RD Adults (n=30)		CAC Adults (n=32)		RLC Children (n=31)	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
<u>Standardized Measures</u>						
Woodcock Word Attack Raw Score	$24.4^{a.}$	6.6	$36.8^{b.}$	4.6	$31.8^{c.}$	7.4
<u>Experimental Measures</u>						
Coltheart Nonwords Strict Accuracy	$0.4^{a.}$	0.2	$0.8^{b.}$	0.1	$0.6^{c.}$	0.2
Lenient Accuracy	$0.5^{a.}$	0.2	$0.9^{b.}$	0.0	$0.8^{c.}$	0.2
Strict Latency (ms)	$1152.3^{a.}$	380.4	$816.0^{b.}$	244.4	$964.9^{a.b.}$	241.9
Lenient Latency (ms)	$1117.9^{a.}$	409.8	$818.1^{b.}$	260.5	$964.3^{a.b.}$	246.1
Rosner AAT	$22.3^{a.}$	8.2	$34.4^{b.}$	6.1	$29.5^{c.}$	7.8
Phonological Choice	$19.8^{a.}$	4.1	$24.8^{b.}$	2.1	$23.2^{b.}$	2.9

Note: Means with different superscripts differ significantly.

Table 4 displays the comparisons between the groups of RD adults, CAC adults, and RLC children on measures of orthographic knowledge. Significant group differences were found on both measures of orthographic knowledge: the spelling subtest of the WRAT3, $\underline{F}(2, 90) = 66.97$, $\underline{p}<.001$, and the Orthographic Choice Task, $\underline{F}(2,90) = 13.12$, $\underline{p}<.001$. However, Scheffe post-hoc tests revealed different patterns of results for the two measures. The spelling test revealed that the performance of CAC adults was superior to that of both RD adults and RLC children, but the RD and RLC groups did not differ significantly. This pattern results from the fact that the WRAT-3 spelling test is not a pure orthographic measure, but is heavily influenced by phonological processing. However, for the purpose of this study, the spelling test was considered an orthographic measure. In contrast, RD adults made word-likeness judgments as successfully as CAC adults on the Orthographic Choice task. The RLC children performed more poorly than both groups of adults on this task. This pattern is thought to reflect that orthographic processing loads more heavily on this test than phonological processing. Significant group differences were also found between RD and CAC adults for performance on the Magazine Recognition Questionnaire, the measure of exposure to print, $t(57) = 3.73$, $p<.001$, which has been found to predict orthographic processing (Barker, Torgesen & Wagner, 1992; Stanovich & West, 1989).

Table 4: Group Comparisons on Standardized and Experimental Measures of Orthographic Knowledge and Print Exposure

	RD Adults (n=30)		CAC Adults (n=32)		RLC Children (n=31)	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
WRAT3 Spelling Raw Score	30.63$^{a.}$	5.61	44.44$^{b.}$	4.35	31.00^{ba}	6.10
Orthographic Choice	14.53$^{a.}$	1.59	15.50$^{a.}$	0.95	13.16$^{b.}$	2.56
Magazine Recognition Questionnaire	21.67$^{a.}$	13.41	54.64$^{b.}$	14.66		

Note: Means with different superscripts differ significantly.

The next series of ANOVAs that was conducted compared the performance of the RD, CAC and RLC groups on the first set of the timing variables. This set was composed of variables that involved perception in the auditory, visual, and tactile domains. Table 5 presents the groups means on each measure of perception. In the task of simple auditory perception, the Auditory Gap Detection, the sensitivity (as indicated by d') of the groups differed significantly when the ISI was short, $F(2,87) = 3.88$, $p<.05$, when the ISI was of intermediate duration, $F(2,87) = 13.67$, $p<.001$, and when it was long, $F(2,87) = 12.29$, $p<.001$. Scheffe post-hoc tests revealed that RLC children performed more poorly than CAC adults at the short ISI, and more poorly than both groups of adults at the medium and long ISIs. However, the sensitivity of RD adults in the auditory gap detection tasks did not differ from the CAC adults at any ISI. In fact, a group (3; RD vs. CAC vs. RLC) by ISI (3; short vs. medium vs. long) repeated measures ANOVA was conducted to determine whether the pattern of results predicted by the temporal processing deficit hypothesis (i.*e.*, that RD adults would perform more poorly than CA controls with short ISIs but not when the ISI is long). Both the main effect of group, F(2,86)=10.09, p<.001, and the main effect of ISI, F(2,172)=47.54, p<.001 were significant. The group by ISI interaction was also significant, F(4,172)=5.84, p<.01. However, the interaction was not in the direction predicted by the temporal processing deficit hypothesis (*i.e.* the performance of dyslexic adults would be significantly worse than CA adults when the ISI is short but not when it is long). Instead, both RD and CAC adults were less sensitive with short ISIs than with ISIs of medium or long duration. In contrast, RLC children were equally sensitive across the three ISIs. A similar pattern of results was found for the task of simple visual perception. For the Visual Gap Detection, the sensitivity of the groups differed significantly when the ISI was short, F(2,85) = 14.18, p<.001, when the ISI was of intermediate duration, F(2,85) = 10.89, p<.001, and when it was long, F(2,85) = 8.29, p<.001. However, Scheffe post-hoc tests revealed a different pattern of performance. RLC children were less sensitive than CAC adults at each ISI. RD adults were significantly less sensitive than CAC adults only when the ISI was short. However, a group (3; RD vs. CAC vs. RLC) by ISI (3; short vs. medium vs. long) repeated measures ANOVA revealed significant main effects of both group, F(2,85) = 12.04, p<.001, and ISI, F(2,170) = 9.38, p<.001, but the group by ISI interaction failed to reach significance, F(4,170) = 1.29, ns. Thus, the interaction predicted by the temporal processing deficit hypothesis was not produced. The three groups' latencies differed significantly in both the auditory gap detection task, F(2,86) = 26.6, p<.001, and the visual gap detection task, F(2,85) = 29.32, p<.001. For both modalities, Scheffe post-hoc analysis revealed that CAC adults responded faster than RD adults, who, in turn, performed more quickly than RLC children. This pattern contrasts with the latencies in the pseudoword reading task, in which RD adults were slower than RLC children. The final task of simple perception, the Finger Localization Task, failed to reveal group differences, F(2,85) = 1.939, ns. However, on the complex task of auditory perception, the Seashore Rhythm Test, CAC adults performed significantly better than RD adults, t(57) = 3.807, $p<.001$.

Table 5: Group Comparisons on Timing Tasks Involving Perception

	RD Adults (n=29)		CAC Adults (n=32)		RLC Children (n=29)	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
Auditory Gap Detection						
Short ISI (d')	2.24$^{a.b.}$	1.14	2.60$^{a.}$	0.96	1.81$^{b.}$	1.22
Medium ISI (d')	2.94$^{a.}$	1.22	3.30$^{a.}$	0.81	1.92$^{b.}$	1.12
Long ISI (d')	2.99$^{a.}$	1.22	3.37$^{a.}$	0.83	2.06$^{b.}$	1.09
Overall RT (ms)	705.22$^{a.}$	150.37	562.31$^{b.}$	129.62	840.68$^{c.}$	163.53
Seashore Rhythm Test	24.79$^{a.}$	3.37	27.57$^{b.}$	2.10		
Visual Gap Detection						
Short ISI (d')	2.62$^{a.}$	1.03	3.30$^{b.}$	0.76	2.03$^{a.}$	0.96
Medium ISI (d')	2.91$^{a.b.}$	1.10	3.47$^{a.}$	0.72	2.29$^{b.}$	1.05
Long ISI (d')	2.82$^{a.b.}$	1.12	3.31$^{a.}$	0.73	2.31$^{b.}$	0.96
Overall RT (ms)	584.40$^{a.}$	101.90	492.74$^{b.}$	94.99	729.66$^{c.}$	155.55
Finger Localization	27.75$^{a.}$	2.47	28.52$^{a.}$	1.34	27.59$^{a.}$	1.96

Note: Means with different superscripts differ significantly.

The next set of timing variables investigated with a series of ANOVAs and t-tests compared the performance of the three groups on variables involving the rapid naming of digits. Table 6 summarizes the speed and accuracy with which the three groups named digits. The results from this sample of RD adults converged with those from the majority of other samples in the literature (*e.g.* Bowers & Wolf, 1992). In the continuous, or standard version of the RAN, significant group differences were revealed in mean latencies, F(2,87) = 5.637, $p<.01$, but not in error rates, F(2,89) = 0.849, ns. However, error rates were very low, making it unlikely that group differences would be revealed. Scheffe post-hoc tests revealed that RD adults named digits significantly slower than CAC adults but not RLC children. Although this pattern was replicated in the discrete-trial, or serial version of the RAN when the ISI was long, t(49) = 2.606, p<.05, RD adults' naming speed did not differ from CAC adults when the ISI was short, t(49) = 1.654, ns. Finally, RD adults named digits as accurately as CAC adults when the ISI was both long, t(49) = 1.63, ns, and short, t(49) = 0.391, ns.

Table 6: Group Comparisons on Timing Tasks Involving the Rapid Naming of Digits

	RD Adults		CAC Adults		RLC Children	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
Continuous RAN						
RT (s)	23.3^{a}	4.2	19.5^{b}	4.3	$22.4^{a,b}$	5.3
Errors	0.1	0.4	0.0	0.2	0.2	0.5
Discrete RAN: Long ISI						
RT (ms)	599.0^{a}	79.6	544.0^{b}	70.1		
Errors	0.1^{a}	0.4	0.0^{a}	0.1		
Discrete RAN: Short ISI						
RT (ms)	520.6^{a}	128.7	467.9^{a}	98.9		
Errors	1.4^{a}	2.3	1.2^{a}	2.5		

Note: Means with different superscripts differ significantly.

The third set of timing variables explored with a series of ANOVAs and t-tests were those involving speech production. Table 7 displays the group means for each oral timing task. Although RD adults' maximum repetition rate was slower than that of CAC adults, t(54) = 2.12, p<.05, the accuracy of the two groups did not differ on this task, t(54) = 1.07, ns. A group (2; RD vs. CAC) by speed (2; fast vs. slow) repeated measures ANOVA conducted to investigate the variability (SD) with which participants repeated sets of syllables revealed a significant main effect of group, F(1, 53) = 18.498, p<.001. However, neither the main effect of speed, F(1,53) = 0.833, ns, nor the group by speed interaction, F(1,53) = 0.827, ns, were significant. A second 2 (group) by 2 (speed) repeated measures ANOVA was conducted to investigate the errors committed on the syllable repetition task. In addition to a significant main effect of group, F(1,53) = 23.45, p<.0001, both the main effect of speed, F(1,53) = 25.796, p<.0001, and the group by speed interaction, F(1,53) = 9.854, p<.005, were significant. Finally, a series of t-tests was conducted to examine the success with which RD and CAC repeated syllables at the prescribed rate. The RD adults repeated the sets of two syllables more slowly than CAC adults at both the fast rate (326 ms/set), t(53) = 3.02, p<.005, and the slow rate (556 ms/set), t(53) = 2.75, p<.01. When the sets of three syllables were repeated, RD adults were slower than CAC adults for the fast prescribed rate (462 ms/set), t(53) = 5.40, p<.0001, but not the slow repetition rate (1.73 ms/set), t(53) = 1.73, ns.

Table 7: Group Comparisons on Timing Tasks Involving Speech Production

	RD Adults		CAC Adults	
	Mean	S.D.	Mean	S.D.
MRR: Repetitions	19.45^{a}	3.89	21.42^{b}	3.05
Errors	0.11	0.16	0.17	0.29
Syllable Repetition				
SD: Fast	85.37^{a}	43.63	48.79^{b}	17.48
SD: Slow	85.03^{a}	36.75	55.90^{b}	27.29
Errors: Fast	2.27^{a}	1.58	0.51^{b}	0.83
Errors: Slow	1.03^{a}	1.47	0.19^{b}	0.31
Rate: Fast 2 syllables (ms)	518.74^{a}	127.54	402.42^{b}	48.88
Rate: Slow 2 syllables (ms)	677.60^{a}	137.43	607.25^{b}	26.38
Rate: Fast 3 syllables (ms)	777.86^{a}	203.40	568.05^{b}	58.25
Rate: Slow 3 syllables (ms)	928.89	172.67	873.98	20.34

Note: Means with different superscripts differ significantly.

The final set of timing variables explored with a series of ANOVAs and t-tests were those involving manual coordination. Table 8 displays the group means for each manual timing task. Although no group differences were revealed in the Placing Pennies in a Box task, F(2,87) = 2.044, ns, RD adults performed more poorly than CAC adults on the remaining tasks. That is, RD adults were less successful than CAC adults at simultaneously drawing lines and crosses, *t*(57) = 3.731, *p*<.001. A group (2: CAC vs. RD) by speed (2; fast vs. slow) repeated measures ANOVA conducted to investigate tapping variability revealed a significant main effect of group, *F*(1, 59) = 20.8, *p*<.001. However, neither the main effect of speed, *F*(1,59) = 1.88, *ns*, nor the group by speed interaction, *F*(1,59) = 2.26, *ns*, were significant. A second group (2) by speed (2) repeated measures ANOVA was conducted to investigate the errors committed on the tapping task. Once again, a significant main effect of group was revealed, *F*(1,59) = 11.05, *p*<.005, but neither the main effect of speed, *F*(1,59) = 0.12, *ns*, nor the group by speed interaction, *F*(1,59) = 0.74, *ns*, were significant. Finally, a series of t-test was conducted to examine the success with which RD and CAC tapped at the prescribed rate. The two groups maintained the prescribed tapping rate with equal success when the prescribed tapping rate was fast (667 ms/finger), *t*(59) = 1.24, *ns* However, when the prescribed tapping rate was slower (1334 ms/finger), RD adults tapped significantly faster than CAC adults, *t*(59) = 3.83, *p*<.001.

Table 8: Group Comaprisons on Timing Tasks Involving Manual Coordination

	RD Adults		CAC Adults		RLC Children	
	Mean	S. D.	Mean	S. D.	Mean	S. D.
Pennies in a Box	8.39	1.55	9.06	1.44	9.23	1.98
Lines and Crosses	9.62^{a}	3.08	12.60^{b}	3.06		
Tapping						
IRI: Fast	124.32^{a}	70.67	71.04^{b}	64.95		
IRI: Slow	161.19^{a}	117.34	69.66^{b}	49.66		
Errors: Fast	2.60^{a}	1.70	1.79^{b}	1.56		
Errors: Slow	2.77^{a}	2.56	1.42^{b}	0.78		
Rate: Fast (ms)	686.99	131.35	721.33	78.79		
Rate: Slow (ms)	1193.10^{a}	186.86	1332.18^{b}	75.64		

Note: Means with different superscripts differ significantly.

Zero-Order Correlations

Table 9 presents the Pearson product-moment correlations for the variables testing reading skill, phonological processing and orthographic processing. Correlational analyses were conducted using the raw scores on standardized measures, and the accuracy and latencies of experimental measures. Because of missing data, some of the correlations reported below have N's less than 62. The results of the correlational analyses revealed high correlations between the accuracy measures of word reading tasks (range: r = .83 to r = .95), and moderate to high correlations among measures of word reading speed and accuracy (range: rs = .56 to .70 in absolute magnitude). Pseudoword and word reading measures were all highly correlated with each other (range: r = .75 to r = .83). The standardized reading comprehension measure, the Nelson-Denny, displayed moderate to high correlations with the participants' accuracy in word and nonword reading tasks (range: rs = .67 to .79).

Performance on the two phonological processing tasks, the Rosner AAT and the Phonological Choice task, were moderately correlated (r = .58). The phoneme segmentation task displayed moderate to high correlations with the word and pseudoword reading measures (range: .62 to .73), although it showed moderate correlations with word reading (r = -.38) and pseudoword reading speed (r = -.40). However, the Phonological Choice revealed moderate to high correlations with word and pseudoword reading measures of accuracy (range: rs = .57 to .72), but was not significantly correlated with word and pseudoword reading speed (rs = -.22 and -.15, respectively). Performance on both phonological processing tasks revealed moderate to high correlations with reading comprehension (rs = .53 and .62).

Table 9: Intercorrelations Among Reading Measures and Measures Testing Phonological and Orthographic Processing for RD and CAC Adults (N=62)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Reading Measures											
1. WRAT3 Reading											
2. Word Identification	.95◆										
3. Nelson-Denny	.79◆	.77◆									
4. Colt. Words (acc)	.83◆	.86◆	.69◆								
5. Colt. Words (RT)	-.66◆	-.70◆	-.57◆	-.56◆							
Phonological Measures											
6. Word Attack	.83◆	.80◆	.65●	.77◆	-.47◆						
7. Colt. Nonword (acc)	.81◆	.82◆	.67◆	.75◆	-.69◆	.78◆					
8. Colt. Nonword (RT)	-.56◆	-.60◆	-.48◆	-.39✣	.72◆	-.41◆	-.60◆				
9. Rosner AAT	.66◆	.65◆	.62◆	.62◆	-.38✣	.73◆	.71◆	-.40✣			
10. Phonological Choice	.60◆	.64◆	.53◆	.67◆	-.22	.72◆	.57◆	-.15	.58◆		
Orthographic Measures											
11. WRAT3 Spelling	.88◆	.73◆	.74◆	.76◆	-.59◆	.73◆	.75◆	-.57◆	.65◆	.50◆	
12. Orthographic Choice	.25*	.23	.38✣	.25*	-.08	.25*	.32*	-.18	.33✣	.34✣	.34✣
13. MRQ	.83◆	.80◆	.79◆	.72◆	-.52◆	.72◆	.72◆	-.48◆	.67◆	.57◆	.79◆

* p<.05; ✣ p<.01; ◆ p<.001

Finally, the correlations involving measures of orthographic processing were suggestive of two underlying constructs. Although spelling performance and print exposure were highly correlated (r = .79), they showed low correlations with word-likeness judgments (rs = .34 and .29, respectively). The low correlation of the former tasks with the Orthographic Choice task is a likely result of their moderate to high correlations with measures of phonological processing (range: r = .48 to .75). In contrast, the correlations between the Orthographic Choice task and measures of phonological processing were much lower (range: r = .18 to r = .34 in absolute magnitude). Similarly, the reading measures produced moderate to high correlations with the spelling and print exposure measures (range: rs = -.52 to .88 in absolute magnitude), but much lower correlations with the word-likeness task (range: rs = -.08 to .38 in absolute magnitude). However, the low reliability of the Orthographic Choice task makes it difficult to interpret its low correlations with other tasks.

Table 10 presents the Pearson product-moment correlations for all the major timing variables. Once again, due to missing data some of the correlations are based on Ns lower than

62. Performance on the timing tasks testing perception was inconsistent across tasks, yielding a range of correlations that ranged in size from insignificance to moderate (range: rs = -.01 to -.65). The highest correlations between the perceptual tasks were among the visual and auditory gap detection tasks, yielding a correlation of r = .65 between the latencies of the two tasks, and r = .65 between the sensitivity of participants on the two tasks. However, correlations within the two gap detection tasks (i.e. the sensitivity and response latency for each task) tended to yield low correlations (rs = -.30 and -.14). The Seashore Rhythm test yielded higher correlations with auditory gap detection (rs = .43 and .63 in absolute magnitude) than either visual gap detection (rs = .27 and .41 in absolute magnitude) or the finger localization (r = .25). In fact, the finger localization task tended to yield very low correlations with the other perception variables (range: r = -.01 to r = -.30).

The timing variables within the domain of speech production also yielded low to moderate correlations with one another (range: rs = .02 to .69 in absolute magnitude). Although the latencies of the two naming tasks were moderately correlated (r = .49), their error rates accuracy were uncorrelated (r = -.11). Naming speed was relatively uncorrelated with articulation rate (range: rs = -.09 to -.29), producing a low correlation between serial naming speed and articulation rate (r = -.29). Both serial and continuous naming speed yielded low correlations with performance on the syllable repetition task (r = .30). Although the two measures of the syllable repetition task were moderately correlated (r = .67), only one, repetition variability, was significantly correlated with articulation rate.

The timing variables testing manual coordination also failed to reflect a single construct. Although the two tapping measures were highly correlated (r = .72), tapping performance was unrelated to the other tasks (rs = -.13 and -.17). However, drawing lines and crosses and placing pennies in a box were moderately correlated (r = .36).

Table 10: Intercorrelations Among Primary Timing Variables for RD and CAC Adults (N=62)

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Perception													
1. Audgap d'													
2. Audgap RT	-.30*												
3. Visgap d'	.65◆	-.27*											
4. Visgap RT	-.26*	.65◆	-.14										
5. Seashore	.43◆	-.63◆	.27*	-.41✚									
6. Fingers	-.01	-.30*	.07	-.24	.25*								
Speech													
7. SRAN RT	-.17	.43◆	-.19	.28*	-.28*	-.39✚							
8. SRAN err	-.01	-.10	-.17	.08	.07	.08	.07						
9. DRAN RT	-.20	.51◆	-.13	.33	-.29*	-.42✚	.49◆	.03					
10. DRAN err	-.19	-.02	-.14	.00	.01	-.09	.14	-.11	-.02				
11. MRR	.19	-.27*	.03	-.03	.38✚	.19	-.09	.10	-.29*	-.19			
12. Syllable SD	-.21	.35✚	-.26*	.24	-.43◆	-.16	.07	-.03	.23	.01	-.29*		
13. Syllable err	-.11	.36✚	-.22	.23	-.38✚	-.24	.30*	.15	.30*	-.05	-.13	.67◆	
Manual													
14. Pennies	-.06	-.18	.04	-.31*	.12	.22	-.05	-.01	-.30*	.02	.16	-.29*	-.33✚
15. L & C	.12	-.53◆	.16	-.32*	.20	.42✚	-.34✚	-.15	-.46◆	.06	.23	-.35✚	-.44◆
16. Tapping IRI	-.38✚	.24	-.36✚	.10	-.39✚	-.12	.16	.03	.15	.39✚	-.28*	.56◆	.47◆
17. Tapping err	-.27*	.26*	-.18	.07	-.41✚	-.28*	.21	.13	.24	.44◆	-.31*	.39✚	.41◆

* p<.05; ✚ p<.01; ◆ p<.001

Note:

Audgap = Auditory Gap Detection

Visgap = Visual Gap Detection

Seashore = Seashore Rhythm Test

Fingers = Finger Localization

SRAN = Standard (continuous) RAN

DRAN = Discrete-trial (serial) RAN

MRR = Maximum Repetition Rate

Pennies = Placing Pennies in a Box

L & C = Drawing Lines and Crosses

Table 10 is continued on the next page.

Table 10: Intercorrelations Among Primary Timing Variables for RD and CAC Adults (cont.)

	14.	15.	16.
Manual			
14. Pennies			
15. L & C	.36✢		
16. Tapping IRI	-.13	-.17	
17. Tapping err	.00	-.22	.72◆

* p<.05; ✢ p<.01; ◆ p<.001

In addition to the three domains showing little internal consistency, correlations also tended to be low across modalities. For example, sensitivity as measured by d' on both gap detection tasks, in addition to response latencies in the visual task were uncorrelated with each of the speech production variables (range: r = .00 to r = .28). In contrast, response latencies on the auditory gap detection task yielded moderate correlations with naming speed (rs = .43 and .51) and low to moderate correlations with articulation rate and syllable repetition (range: rs = .27 to .36 in absolute magnitude). Performance on the Seashore Rhythm Test also yielded low to moderate correlations with naming speed, articulation rate and syllable repetition (range: r = -.28 to r = -.43).

Performance on tasks testing manual coordination also tended to be unrelated with the perceptual tasks. The tapping measures produced low to moderate correlations with sensitivity as measured by d' on both gap detection tasks, and performance on the Seashore Rhythm Test (range: r = -.18 to r = -.41). In contrast, simultaneously drawing lines and crosses was moderately correlated with response latencies in the gap detection tasks and finger localization (range: r =.32 to r = .42 in absolute magnitude).

Finally, speech production and motor coordination also tended to produce relatively few significant correlations. Performance on the syllable repetition task was moderately correlated with performance on the tapping task, in addition to the measures of manual coordination (range: rs = .29 to .56 in absolute magnitude). Both tapping measures were moderately coordinated with articulation rate (rs = -.28 and -.31) and the number of errors committed in the discrete-trial RAN (rs = .39 and .44). Naming speed in the discrete-trial task also produced moderate to low correlations with placing pennies in a box and drawing lines and crosses (rs = -.30 and -.46).

The correlations between the experimental timing tasks and the reading / phonological measures are presented in Table 11. In general, the timing tasks correlated better with the academic measures than they did with each other. Of the perceptual timing measures, response latencies in the auditory gap detection task produced the highest correlations with the readings measures (range: rs = .43 to .54 in absolute magnitude), phonological processing variables (range: rs = -.30 to -.59), and orthographic measures (range: rs = -.43 to -.49). Performance on the Seashore Rhythm Test yielded a similar pattern of correlations, with low to moderate correlations with measures of reading accuracy (range: rs = .29 to .51), accuracy measures in phonological processing (range: rs = .38 to .56), and orthographic measures (range: rs = .38 to .45). Similarly, visual gap detection latencies yielded low to moderate correlations with reading measures (range: r = -.26 to -.46), accuracy in pseudoword reading and phoneme segmentation (range: r = -.33 to r = -.49), spelling, and print exposure (rs = -.40 and -.32). Although sensitivity, as measured by d', in the visual gap detection task produced low correlations with standardized reading measures (rs = .25 and .26), it yielded low to moderate correlations with all measures of phonological processing (range: rs = .30 to .40) and low correlations with word-likeness judgments and exposure to print (rs = .31 and -.32). Neither finger localization nor sensitivity (d') correlated well with academic measures.

Two types of speech production variables tended to correlate well with academic measures. Although continuous naming speed correlated with academic measures better than serial naming speed, naming speed produced moderate correlations with reading skill (range: rs = -.29 to -.54), and phonological processing (range: rs = .28 to .49 in absolute magnitude). However, only measures of continuous naming speed correlated with spelling and print exposure (rs = -.53 and -.39). Performance on the syllable repetition task also produced low to moderate correlations with most measures of reading skill (range: r = .32 to r = .56 in absolute magnitude), and phonological processing (range: r = .25 to r = .62 in absolute magnitude). Both

Table 11: Correlations Between Timing and Reading / Phonological / Orthographic Variables for RD and CAC Adults (N=62)

	WRAT3 Read	Word Ident	Nelson-Denny	Colt. Word (d')	Colt. Word (RT)	Word Attack	Colt. Nonword (d')	Colt. Nonword (RT)	Rosner AAT	Phon. Choic
Perception										
1. Audgap d'	.11	.12	.17	.14	-.01	.22	.23	.11	.34✚	.11
2. Audgap RT	-.54♦	-.51♦	-.51♦	-.48♦	.43♦	-.59♦	-.56♦	.35✚	-.50♦	-.30*
3. Visgap d'	.25*	.26*	.21	.24	-.08	.36✚	.30*	.40✚	.32*	.30*
4. Visgap RT	-.36✚	-.26*	-.46♦	-.27*	.37✚	-.33✚	-.49♦	.07	-.39✚	-.14
5. Seashore	.42♦	.37✚	.51♦	.29*	-.16	.52♦	.39✚	-.23	.56♦	.38✚
6. Fingers	.32*	.23	.29*	.30*	.00	.35✚	.21	-.03	.39✚	.34✚
Speech										
7. SRAN RT	-.54♦	-.51♦	-.41♦	-.53♦	.42♦	-.49♦	-.48♦	.28*	-.48♦	-.32✚
8. SRAN err	-.13	-.15	-.19	-.24	.14	-.11	-.28*	.21	-.13	-.28*
9. DRAN RT	-.32*	-.29*	-.14	-.35✚	.37✚	-.44♦	-.41♦	.28*	-.36✚	-.19
10. DRAN err	.05	.01	.04	.06	-.14	.02	.04	-.20	-.15	.06
11. MRR	.19	.12	.24	-.01	-.03	.20	.11	-.12	.23	.07
12. Syllable SD	-.48♦	-.44♦	-.32*	-.38✚	.24	-.41♦	-.45♦	.25*	-.43♦	-.28*
13. Syllable err	-.56♦	-.52♦	-.40✚	-.45♦	.32*	-.46♦	-.62♦	.43♦	-.50♦	-.41✚
Manual										
14. Pennies	.13	.07	.11	.07	-.01	.05	.21	-.20	.20	.06
15. L & C	.45♦	.39✚	.49♦	.43♦	-.30*	.46♦	.47♦	-.19	.50♦	.33✚
16. Tapping IRI	-.40✚	-.41♦	-.35✚	-.36✚	.10	-.39✚	-.43♦	.15	-.36✚	-.32*
17. Tapping err	-.33✚	-.33✚	-.33✚	-.38✚	.05	-.45♦	-.37✚	.15	-.42♦	-.39✚

* p<.05; ✚ p<.01; ● p<.001

Note: Colt. = Coltheart

Audgap = Auditory Gap Detection

Visgap = Visual Gap Detection

Seashore = Seashore Rhythm Test

Fingers = Finger Localization

SRAN = Standard (continuous) RAN

DRAN = Discrete-trial (serial) RAN

MRR = Maximum Repetition Rate

Pennies = Placing Pennies in a Box

L & C = Drawing Lines and Crosses

Table 11 is continued on the next page.

Table 11: Correlations Between Timing and Reading / Phonological / Orthographic Variables for RD and CAC Adults (continued)

	WRAT3 Spelling	Ortho. Choice	MRQ
Perception			
1. Audgap d'	.14	.42✚	.05
2. Audgap RT	-.49◆	-.43◆	-.46◆
3. Visgap d'	.16	.31*	.40✚
4. Visgap RT	-.40✚	-.23	-.32*
5. Seashore	.44◆	.38✚	.45◆
6. Fingers	.32*	.19	.26*
Speech			
7. SRAN RT	-.53◆	-.19	-.39✚
8. SRAN err	-.17	-.29*	-.17
9. DRAN RT	-.21	-.18	-.23
10. DRAN err	.06	-.06	.11
11. MRR	.13	.12	.13
12. Syllable SD	-.43◆	-.06	-.52◆
13. Syllable err	-.51◆	-.22	-.54●
Manual			
14. Pennies	.11	.07	.08
15. L & C	.35✚	.34✚	.37✚
16. Tapping IRI	-.45◆	-.28*	-.34✚
17. Tapping err	-.33✚	-.29*	-.31*

* p<.05; ✚ p<.01; ◆ p<.001

syllable repetition variables yielded moderate correlations with spelling and print exposure (range: r = -.43 to -.54). Articulation rate was uncorrelated with the academic variables.

Finally, the relationship between the timing variables involving manual coordination and academic performance was examined. Although success at simultaneously placing pennies in boxes was uncorrelated with the academic variables, skill at simultaneously drawing lines and crosses produced moderate correlations with all reading measures (range: rs = -.30 to .49), accuracy in phonological processing (range: rs = .33 to .50), and orthographic processing (range: rs = .34 to .37). Both variables from the tapping task produced low to moderate correlations with the accuracy measures in reading (range: r = -.33 to r = -.41), accuracy measures in phonological processing (range: r = -.32 to -.45), and all measures of orthographic processing (range: r = -.28 to r = -.45).

Regression Analyses

A series of regression analyses was conducted using the experimental timing tasks to predict the adults' reading performance, independently of phonological processing, as measured by their raw scores on the standardized reading measures (WRAT3 and Woodcock Word Identification), and their accuracy and latencies on the experimental words. In the analyses, the Rosner AAT was forced into the equation as the first predictor. After the Rosner had been forced into the equation, stepwise analysis was used to select the most potent stepwise predictors. The four regression analyses yielded the same pattern of results. The results from the WRAT3 will be presented in detail. Table 12 clearly shows that once phonological processing in the form of the Rosner AAT has been entered into the equation, the only variable that contributed additional variance to word recognition was participants' naming speeds from the Standard RAN (additional variance explained = .13, $p<.01$). In fact, the combination of the Rosner AAT and the Standard RAN accounted for 54% of the variance in predicting performance on the Reading subtest of the WRAT3. No other experimental timing variable contributed additional variance once performance on the Rosner AAT and the Standard RAN had been partialled out.

Tables 12,13 and 14 present the results of the same regression analyses on the three other measures of word recognition, the Woodcock Word Identification, and the speed and accuracy with which the set of experimental words were read. Once performance on the phoneme segmentation task, the Rosner AAT, had been entered as the first step in the regression equation, the 15 experimental timing variables were entered into the equations. The only significant predictor of the three criterion measures was the Standard RAN even after phonological processing had been partialled out (additional variance explained = .08 to .14). No other timing variable was predictive of word recognition.

Table 12: Regression Analysis Predicting Adults' WRAT3 Reading Performance (N=41)

Step Variable	Mult R	Mult R^2	R^2 Change	Partial R	F Ratio	P
Rosner AAT (forced)	.635	.403	.403		26.310	< .01
Subsequent Variables Stepwise						
Standard RAN (RT)	.731	.535	.132	-.470	10.788	< .05
Discrete-Trial RAN (RT)				.128	.613	ns
Discrete-Trial RAN (err)				.256	2.601	ns
Auditory Gap (d')				-.191	1.398	ns
Auditory Gap (RT)				-.238	2.212	ns
Visual Gap (d')				.032	.039	ns
Visual Gap (RT)				.027	.028	ns
Seashore Rhythm Test				.041	.062	ns
Finger Localization				-.096	.341	ns
Syllable Repetition (err)				-.289	3.384	ns
Syllable Repetition (SD)				-.276	3.047	ns
Tapping (err)				-.027	.028	ns
Tapping (IRI)				-.220	1.884	ns
Drawing Lines & Crosses				.011	.004	ns
Placing Pennies in a Box				-.182	1.261	ns

Table 13: Regression Analysis Predicting Adults' Performance on the Woodcock Word Identification (N=41)

Variable	Mult R	Mult R^2	R^2 Change	F Ratio
Rosner AAT (forced)	.647	.419	.419	28.133
Subsequent Variables Stepwise				
Standard RAN	.733	.537	.118	9.686

Table 14: Regression Analysis Predicting Adults' Performance on Experimental Word List (Accuracy) (N=41)

Variable	Mult R	Mult R^2	R^2 Change	F Ratio
Rosner AAT (forced)	.476	.226	.226	11.411
Subsequent Variables Stepwise				
Standard RAN	.608	.370	.144	8.649

Table 15: Regression Analysis Predicting Adults' Performance on Experimental Word List (Latency) (N=41)

Variable	Mult R	Mult R^2	R^2 Change	F Ratio
Rosner AAT (forced)	.437	.191	.191	8.954
Subsequent Variables Stepwise				
Standard RAN	.522	.273	.082	4.184

Because naming speed as measured by the Standard RAN proved to be a robust predictor of word reading independent of phonological awareness, two additional hierarchical regression analyses were conducted using measures that tap reading behavior indirectly. The criterion variables are WRAT3 Spelling, and the measure of print exposure, the Magazine Recognition Questionnaire. Tables 16 and 17 present the results of the regression analyses using these criterion variables, which converged with those using direct measures of word recognition. Once performance on the Rosner AAT had been entered as the first step in the regression equations, the only one of the 16 timing variables that were entered into the equations was the Standard RAN (additional variance explained on both tasks was .07). No other timing variable was predictive of spelling or print exposure.

Table 16: Regression Analysis Predicting Adults' WRAT3 Spelling Performance (N=41)

Variable	Mult R	Mult R^2	R^2 Change	F Ratio
Rosner AAT (forced)	.664	.441	.441	6.494
Subsequent Variables Stepwise				
Standard RAN	.715	.511	.070	5.484

Table 17: Regression Analysis Predicting Adults' Performance on the Magazine Recognition Questionnaire (N=41)

Variable	Mult R	Mult R^2	R^2 Change	F Ratio
Rosner AAT (forced)	.637	.406	.406	26.633
Subsequent Variables Stepwise				
Standard RAN	.689	.475	.071	5.031

Because the naming speed proved to be a very robust predictor of reading skill, spelling and print exposure, a final stepwise regression analysis was conducted in which the criterion variable was performance on the Standard RAN. Table 18 clearly shows that the variables that explained 48% of the variance of Standard RAN were WRAT3 Reading performance and naming speed in the Discrete-Trial RAN. Neither performance on standardized measures such as the estimated IQ, nor performance on the other experimental timing variables were predictive of naming speed.

Table 18: Regression Analysis Predicting Adults' Performance on the Standard RAN (N=41)

Step Variable	Mult R	Mult R^2	R^2 Change	Partial R	F Ratio	P
1. WRAT3 Reading	.604	.364	.364		20.640	< .01
2. Discrete RAN RT	.693	.480	.124	.427	7.802	< .01
Estimated IQ				-.031	.033	ns
Woodcock Word Attack				.243	2.141	ns
WRAT3 Spelling				.070	.169	ns
Rosner AAT				.044	.066	ns
Orthographic Choice				.039	.051	ns
Discrete RAN errors				.302	3.414	ns
Auditory Gap RT				.040	.055	ns
Auditory Gap d′				-.108	.402	ns
Visual Gap RT				.201	1.437	ns
Visual Gap d′				-.088	.267	ns
Seashore Rhythm Test				.084	.244	ns
Finger Localization				-.050	.085	ns
Syllable Repetition errors				-.184	2.347	ns
Syllable Repetition SD				-.254	1.186	ns
Maximum Repetition Rate				-.144	.724	ns
Tapping IRI				.004	.001	ns
Tapping errors				.151	.791	ns
Lines & Crosses				-.075	.193	ns
Pennies in a Box				.155	.835	ns

Commonality Analyses

The relationships among phonological processing, naming speed, and timing variables was further explored using commonality analysis (see Kerlinger & Pedhazur, 1973). The use of commonality analysis allowed for the examination of the unique and common variance that the three measures contributed to WRAT3 reading performance (Kerlinger & Pedhazur, 1973). Therefore, it was possible to determine the amount of variance that combinations of phonological processing, naming speed, and various timing variables shared in common in predicting raw scores in WRAT3 Reading.

Because variables within each modality tended to share moderate correlations, three timing variables reflecting perception, speech articulation, and motor coordination were constructed. The timing-perception variable was a composite variable based on sensitivity in the visual and auditory gap detection tasks, finger localization and the Seashore Rhythm tests. Timing-perception was calculated as the mean of the z-scores for sensitivity (d') on the visual and auditory gap detection tasks, the z-scores for the finger localization task, and the z-score for the Seashore Rhythm test. For the second timing variable, timing-articulation, the response latency on the Discrete-Trial RAN task, variability (SD) on the syllable repetition task, and the score from the maximum repetition rate were collapsed as a composite z-score. Additionally, the scores in drawing lines and crosses, placing pennies in a box, and the number of errors committed on the tapping task were collapsed as a composite z-score for the third timing variable, timing-manual. Finally, a fourth timing variable, timing-best, was constructed in order to magnify the variance explained by the timing variable. This variable was the standardized composite score of the experimental timing variables that had the highest zero-order correlations with WRAT3 reading performance: the latency for the auditory gap detection task, the number of errors committed on the syllable repetition task, and the score for drawing lines and crosses. In each of the four composite timing variables, the scores were standardized and averaged.

The amount of unique variance contributed by phonological processing, the Standard RAN, and each of the timing variables was calculated using a series of hierarchical regression procedures. For each variable, the amount of total shared variance was decomposed into unique variance and variance shared with each of the other measures. For example, the covariance relationships between the Rosner AAT, Standard RAN, and Timing-Perception are explored in Table 19. Phoneme segmentation displayed a squared multiple correlation with WRAT3 Reading of .460. This 46% variance in word recognition explained by the Rosner AAT is decomposed into 16.6% unique variance, 7.3% variance shared with the Standard RAN, 5.7% variance shared with the timing-perception variable, and 16.4% variance shared with both the Standard RAN and the timing-perception variables. The Standard RAN displayed a squared multiple correlation with WRAT3 Reading of .315. The 31.5% variance in word recognition explained by the Standard RAN accounted for 7.7% unique variance, 7.3 % variance shared with the Rosner AAT, 0.1% variance shared with the timing-perception variable, and 16.4% variance shared with the two other variables. Finally, the timing-perception variable displayed a squared multiple correlation with WRAT3 Reading of .222. Although timing perception shared 5.7% variance with the Rosner AAT, 0.1% variance with naming speed, and 16.4% variance with both variables, it did not account for any unique variance (0%) in predicting word recognition.

Very similar patterns of unique and common overlapping variances were produced among the Rosner phoneme segmentation task, Standard RAN, and the three remaining timing variables. These patterns are presented in Tables 20, 21 and 22. For example, the unique variance explained by the Rosner AAT ranged from 16.6% to 21.8% on the timing tasks, while the Standard RAN accounted for 6.5% to 7.7% unique variance. In contrast, the three timing composites failed to explain more than 3.3% unique variance. The amount of variance shared between the Standard RAN and the Rosner AAT ranged between 7.3% and 22.4% of the variance The timing composites tended to share little overlapping variance with either the Rosner AAT (range: R^2=-.005 to .057) or the Standard RAN (range: R^2=.001 to .013). Finally, the amount of variance shared between the three variables ranged from 1.3% to 16.4%.

Table 19: Commonality Analysis Using WRAT3 Reading Subtest as Criterion Variable

	Predictor Variables		
	Rosner	RAN	Timing (Perception)
Unique Variance	.166	.077	.00
Common to Rosner and RAN	.073	.073	
Common to Rosner and Timing	.057		.057
Common to RAN and Timing		.001	.001
Common to Rosner, RAN, and Timing	.164	.164	.164
Total R^2 for variable	.460	.315	.222

Note: The Timing (Perception) variable is the z-score composite of participants' scores in gap detection (mean d′ on both auditory and visual gap detection), finger localization, and the Seashore rhythm test.

Table 20: Commonality Analysis Using WRAT3 Reading Subtest as Criterion Variable

	Predictor Variables		
	Rosner	RAN	Timing (Articulation)
Unique Variance	.129	.067	.028
Common to Rosner and RAN	.125	.125	
Common to Rosner and Timing	.079		.079
Common to RAN and Timing		.008	.008
Common to Rosner, RAN, and Timing	.100	.100	.100
Total R^2 for variable	.433	.300	.215

Note: The Timing (Articulation) variable is the z-score composite of participants' scores in Discrete-Trial RAN (RT), Syllable Repetition (SD), and the reflected Maximum Repetition Rate (number repetitions).

Table 21: Commonality Analysis Using WRAT3 Reading Subtest as Criterion Variable

	Predictor Variables		
	Rosner	RAN	Timing (Manual)
Unique Variance	.155	.072	.012
Common to Rosner and RAN	.118	.118	
Common to Rosner and Timing	.062		.062
Common to RAN and Timing		.009	.009
Common to Rosner, RAN, and Timing	.089	.089	.089
Total R^2 for variable	.424	.288	.172

Note: The Timing (Manual) variable is the z-score composite of participants' scores in Drawing Lines and Crosses, Placing Pennies in a Box, and Tapping (reflected errors).

Table 22: Commonality Analysis Using WRAT3 Reading Subtest as Criterion Variable

	Predictor Variables		
	Rosner	RAN	Timing (Best)
Unique Variance	.140	.050	.036
Common to Rosner and RAN	.079	.079	
Common to Rosner and Timing	.066		.066
Common to RAN and Timing		.028	.028
Common to Rosner, RAN, and Timing	.119	.119	.119
Total R^2 for variable	.460	.315	.249

Note: The Timing (Best) variable is the z-score composite of participants' scores in the three timing variables with the highest zero-order correlations with WRAT3 Reading: Auditory Gap Detection (RT), Syllable Repetitition (Errors), and the reflected score from Drawing Lines and Crosses.

Discussion

The present discussion is organized in four main sections. The first section examines the nature of temporal processing deficits in reading disability. This section explores whether adults with dyslexia show any deficits in temporal processing tasks. In the second section, the relationship between deficient temporal processing, reading skill and the phonological core deficit associated with developmental dyslexia will be explored. In the third section, an attempt is made to place the results within the broader context of current theories of developmental dyslexia. The suggestion is made and examined that despite dyslexics' poor performance on tasks involving precise temporal processing, reading disability reflects linguistic deficits rather than impaired temporal resolution. The fourth section suggests future directions for research, and limitations to the current study.

The Nature of Temporal Processing Deficits in Developmental Dyslexia

The purpose of this section is to determine whether temporal processing deficits characterize developmental dyslexia. Recall that three different approaches have been used to link temporal processing deficits with developmental dyslexia. The first hypothesis, which proposes that auditory processing deficits underlie dyslexia (e.g., Tallal, 1984), predicts impaired performance by dyslexics on tasks involving auditory perception paired with normal performance on timing tasks in all other domains. The second hypothesis proposes that developmental dyslexia results from impaired temporal resolution in perception in both the auditory and visual domains (e.g., Farmer & Klein, 1995). Support for this hypothesis would be derived from a pattern of results in which disabled readers' performance is worse than normal readers on tasks involving visual and auditory perception, but matches the performance of normal readers on tasks involving speech production and motor coordination. Finally, the third timing hypothesis advocated a defective domain-general timing mechanism as the cause of reading behavior (e.g. Wolff et al., 1990a, 1990b), which would result in impaired performance in perception, speech production and motor coordination.

On examination of group differences, the results of the present study tend to support the existence of temporal processing deficits across domains. Adults with developmental dyslexia performed more poorly than normal adults on tasks involving perception, speech production and manual coordination. In the domain of perception, although dyslexic adults showed evidence of slower rates of auditory and visual processing than normal adults, they were both faster and more accurate than reading-level matched children in the gap detection tasks. Although they did not require longer ISIs than normal readers to distinguish the two-item stimuli from the uninterrupted single-item stimuli, disabled readers made these judgments more slowly. Although the current study failed to replicate the group by ISI interaction that has been used as evidence for auditory and visual processing deficits (e.g. Di Lollo et al., 1983; Lovegrove et al., 1986; McCroskey & Kidder, 1980), an older sample participated. In fact, most studies that revealed that dyslexics required longer critical ISIs to detect gaps in stimuli used children as participants, and not adults. One might argue that with older samples, auditory and visual processing deficits may diminish so that they can be detected through longer response latencies rather than accuracy. However, the failure to find a group by ISI interaction despite overall poorer performance by disabled readers is consistent with Kruk's (1991) findings. Although Kruk's studies involved children whose ages ranged between 8 and 11 years of age, significant group by SOA interactions were <u>not</u> revealed despite significant group differences. Therefore, age differences between the current sample and the samples in which temporal processing deficits were detected cannot explain the inconsistent results.

However, differences in the measures of sensitivity may explain why the current study failed to replicate the group by ISI interaction that has been used as evidence for auditory and visual processing deficits (e.g. Di Lollo et al., 1983; Lovegrove et al., 1986; McCroskey & Kidder, 1980). Earlier studies, such as those of Lovegrove and his colleagues, used the method of thresholds to establish visible persistence (Lovegrove et al., 1986; Slaghuis & Lovegrove, 1986). Recall that the use of thresholds as measures of perceptual sensitivity is problematic because response thresholds may be influenced by a variety of factors, such as the individual's response bias

(Corso, 1963). Because separation thresholds vary as a function of a variety of factors, it is unclear whether disabled readers' higher separation thresholds reflect perceptual deficits, more stringent criteria to report the presence of flickers, or different response biases. In other words, one cannot be sure that the longer visible persistence of disabled readers in these studies reflect perceptual deficits (*e.g.* Lovegrove et al., 1986; Slaghuis & Lovegrove, 1986; Stanley & Hall, 1973). In contrast, the current study used signal-detection theory's d-prime as a measure of sensitivity because it is able to separate the observer's sensitivity from response bias (Tanner and Swets, 1954). Therefore, one can be sure that the absence of group by ISI interactions in the gap detection tasks is based on the perceptual skills of the participants.

In addition to slower stimulus individuation, dyslexics discriminated auditory rhythmic patterns less successfully than normal readers. The finding that dyslexic adults made more errors in discriminating variations in auditory rhythmic pattern is consistent with similar studies (McGivern et al., 1991; Zurif & Carson, 1970). Therefore, both the Seashore Rhythm Test and latencies in individuation tasks successfully discriminated between dyslexics and normal readers.

Dyslexics also performed more poorly than normal readers in tasks involving speech production. Dyslexic adults had difficulty both naming digits and synchronizing the repetition of nonsense syllables strings with an external timing device. The results of the standard, or continuous RAN was consonant with a growing body of evidence (e.g., Badian, 1993; Bowers & Wolf, 1993; Denckla & Rudel, 1976; Wolff et al., 1990a) suggesting that dyslexics retrieve words more slowly than normal readers. However, of the two rates of presentation for the discrete-trial, or serial RAN, only one - the slow rate - yielded significant differences between dyslexics and adult normal readers. This pattern is the opposite of other similar studies, in which dyslexics showed no naming impairments when stimuli were presented slowly, but were penalized by rapid presentation (Bowers & Swanson, 1991; Wolff et al., 1990). One reason for the discrepency between the current study and the findings of similar studies may result from the different means of collecting responses. In other studies (*e.g.* Bowers, 1995; Bowers & Swanson, 1991; Wolff et al., 1990), presentation of the target symbol was terminated by voice offset, which ensured accurate measurement of the time required to name each item. However, due to technical limitations, the presentation of digits was terminated by voice onset. Therefore, it was less clear whether the time required to initiate a response for each item reflected the speed of word retrieval or other processes. This was problematic particularly in the short ISI condition, as some of the latencies were under 100 ms. Although this may be problematic in the interpretation of the results in the short ISI condition, Bowers' (1995) findings suggest that the problems in the short ISI condition do not compromise the interpretation of the current study's results. Although Bowers found that the naming speeds of children in second and third grade were slower with short ISIs than long ISIs, older children in the fourth grade showed the opposite pattern. Grade 4 children named symbols faster when the ISI was short than in the long ISI condition. The parallel pattern of results support the validity of the current thesis's findings. Similarly, the discrepancy between the current study and similar studies (Bowers & Swanson, 1991; Wolff et al., 1990a) cannot be attributed to both groups finding the rapid presentation rate too easy, rendering it unable to discriminate between groups because the simpler slow presentation rate successfully discriminated between RD and CAC groups. Nor could this discrepancy be attributed to both groups finding the fast presentation rate too difficult, because they named digits faster when the ISI was short rather than long. The shorter latencies when the ISI was short suggests that despite the technical problems, the results can be interpreted. This pattern also diverges from the pattern reported in similar studies (Bowers & Swanson, 1991; Wolff et al., 1990a). According to these studies, the continuous RAN yielded the slowest naming speeds, while the long ISI of the discrete trial RAN yielded the shortest latencies. In sum, although dyslexic adults tended to name digits more slowly than both adult normal readers and reading-level matched children, the pattern of results does not conform to the pattern predicted by timing deficit hypothesis.

In the syllable repetition task, dyslexic adults repeated syllables too slowly even when asked to track the metronome at the slow rates. Because the slow rates required dyslexics to track the metronome at a speed slower than they actually repeated syllables on the fast trials, their failure to repeat syllables at the prescribed slow rates cannot be attributed to their slower articulation rates. Rather, their performance is likelier to reflect difficulty in coordinating behaviour with an externally assigned rate. Similarly, dyslexic adults were both more variable and committed more errors in the synchronization of syllables with the metronome, reflecting poorer timing precision and accuracy. In fact, the group by rate interaction revealed that dyslexics' performance was impaired by rapid repetition rates to a greater extent than adult normal readers. Although they made more errors when the repetition rate was slow, the increased demands of the fast rate impaired dyslexics' accuracy to a greater extent than normal readers. Although these findings are consistent with those of similar studies (Wolff et al., 1990a), the variability with which dyslexics repeated syllables did not conform to the pattern predicted by the timing deficit hypothesis. Recall that the temporal processing deficit hypothesis predicts that disabled readers will be selectively impaired by rapid task demands. Thus, one would expect dyslexics to be more variable when the repetition rate is fast than slow. However, dyslexics repeated syllables with the <u>same</u> consistency at both the fast and the slow rates. Therefore, there is equivocal support for the hypothesis that disabled readers suffer from an impairment in the ability to regulate speech production at rapid rates. In short, although the two measures of naming speed and syllable repetition successfully differentiated skilled and less skilled readers, in subtle ways they failed to support the timing deficit hypothesis.

In addition to poorer performance on tasks involving perception and speech production, dyslexic adults also performed more poorly on two of the three tasks testing motor coordination. Although dyslexic adults coordinated the simultaneous action of simple motor tasks, such as placing pennies in a box, with equal success as normal readers, the coordination of two different simultaneous actions proved to be troublesome for dyslexics. Similarly, dyslexics were less skilled at coordinating two simple alternating movements, tapping their index fingers in alternation at prescribed rates. Not only did they tap with greater variability, dyslexics also committed more tapping errors. These results are consistent with other similar studies (e.g., Badian & Wolff, 1977; Wolff et al., 1990). However, dyslexics' performance on the tapping task violated predictions of the timing deficit hypothesis in two ways. First, the timing hypothesis predicts that disabled readers' tapping would be less consistent and contain more errors than normal readers when the prescribed rate is fast, but not when it is slow. However, the present study revealed that dyslexics' tapping was not impaired by the increased demands of the fast tapping rate. Therefore, there is little evidence that dyslexics have specific difficulties with rapid manual coordination. Similarly, Wolff and his colleagues (e.g., Wolff et al., 1990) have also argued that dyslexics' temporal processing deficits would be revealed by their tapping rates: dyslexics can tap successfully at the prescribed rate when it is slow, but when the rate is fast, they would tap too slowly. However, this pattern of performance failed to unfold. Not only did dyslexic adults successfully maintain the fast rate with their tapping, they tapped too quickly for the slow tapping rate. In contrast, normal readers successfully maintained both tapping rates. Dyslexics' skill at maintaining the rapid tapping rate, and their excessive haste during the slow rate cannot be reconciled with the predictions of the temporal processing deficit. In sum, dyslexics' performance on tasks involving manual coordination provided equivocal support for the timing deficit hypothesis.

In summary, dyslexic adults did perform more poorly than adult normal readers on most of the tasks designed to test the temporal processing construct. Their overall poor performance on the timing tasks that involved auditory and visual perception, speech production and manual coordination may be interpreted as support for a domain general temporal processing deficit. However, the data renders the existence of a domain-general timing deficit unlikely in three important ways. First, recall that all three versions of the temporal processing deficit hypothesis predict group by rate interactions, with dyslexics' performance showing greater sensitivity to rate than normal readers. They differ only in terms of their specificity. Because they share the same predictions and differ only in the breadth, from here on the terms "temporal processing deficit hypothesis" and "timing hypothesis" refer to all three versions of the hypothesis. Therefore, the failure of the group by rate interactions to reach significance undermines the timing hypothesis. As alluded to above, the timing hypothesis predicts that disabled readers would be selectively penalized on tasks with rapid processing demands, but not when processing rates are slow (Wolff et al., 1990, 1990a, 1990b). However, on several tasks, the critical interaction was not observed. For example, dyslexic adults were equally sensitive in the auditory gap detection task as normal adults whether the ISI was short or long. Similarly, dyslexics named digits as successfully as normal readers in the serial task when the ISI was short, but not when the stimulus presentation rate was slow. The syllable repetition and tapping tasks also failed to produce results consistent with the existence of a temporal processing deficit. Although reading disabled adults were generally less consistent than normal readers on these tasks, their performance was uninfluenced by rate. These results clearly contradict the central assumption of all variations of the temporal processing deficit theory. This assumption is that dyslexics' impairments lie in their inability to process rapidly presented stimuli (Farmer & Klein, 1995; Tallal et al., 1991; Wolff et al., 1990a, 1990b).

Examination of dyslexics' performance relative to younger children matched on their reading level represents a second failure to support the temporal processing deficit of reading disability. Recall that a reading-level matched design enables one to determine whether dyslexics' cognitive abilities develop differently than normal readers, or whether their cognitive abilities follow the same stages of development at a slower rate (Stanovich, Nathan & Vala-Rossi, 1986; Stanovich & Siegel, 1994). This procedure is more selective than chronological-age matched designs, which tend to reveal significant differences on a wide variety of tasks and reduce the diagnosticity of any of these differences (Stanovich, 1986b). In contrast, the reading-level match designs reveal fewer tasks on which dyslexics show inferior performance than reading-level controls, and these differences cannot be the attributed to differences in reading ability (Stanovich & Siegel, 1994).

Use of the reading-level matched design revealed that adult disabled readers were less skilled than reading-level matched children on tests of pseudoword reading and phonological sensitivity. These findings converged with those from the majority of other samples in the literature, showing that the proximal cause of reading disability is deficient phonological processing (Bruck, 1990, 1992; Chiappe, Stanovich & Siegel, 1996; Fowler, 1991; Rack et al., 1995; Share & Stanovich, 1995; Siegel, 1993; Siegel & Ryan, 1988; Stanovich, 1991; Stanovich & Siegel, 1995; Torgesen et al., 1994). The possibility that deficient temporal processing may underlie the phonological deficit, serving as a more distal cause of reading failure, was also examined using the reading-level match design. A pattern supportive of the temporal processing deficit hypothesis would take the form of dyslexic adults showing deficits relative to the reading-level matched children on the timing tasks. This pattern would suggest that dyslexics have a specific deficit in tasks requiring the rapid processing of stimuli, and this deficit, in theory, could account for the phenotypic performance profile of impaired phonological processing. However, dyslexic adults performed at least as well as reading-level matched children on the experimental timing tasks (e.g., auditory and visual gap detection, continuous RAN and placing pennies in a box). In fact, the adult disabled readers showed superior performance to that of reading-level matched children in terms of sensitivity on the auditory gap detection task, and in terms of response latency on both auditory and visual gap detection tasks. Dyslexic adults' superiority on the sensitivity measure (d′) is particularly important because in the case of the latencies there are large maturational effects on nonrelevant components of RT, whereas they receive no artifactual advantage on the sensitivity measure. Thus, there was no evidence of a specific deficit in temporal processing. Because there was no evidence of a temporal processing deficit relative to reading-level matched controls, it cannot be used as an underlying cause of the phonological core deficit. In other words, one cannot use a set of tasks (experimental timing tasks) on which dyslexics performed equally well or better than reading-level matched children as a causal explanation for a set of tasks (phonological processing tasks) on which dyslexics performed worse than reading-level matched controls.

In conclusion,evidence undermining the existence of temporal processing deficits was derived from two types of group comparisons. On the one hand, the prediction that disabled readers would be selectively penalized on tasks with rapid processing demands, but not when processing rates are slow (Wolff et al., 1990a, 1990b) received no support. Although dyslexics tended to perform worse than chronological-age controls, the predicted interaction was not observed. Therefore, dyslexic adults' performance on the experimental timing tasks was uninfluenced by rate. On the other hand, there was no evidence of a temporal processing deficit relative to reading-level matched controls. Because there was no evidence of a specific timing deficit, it cannot be used as a causal explanation for dyslexics' inferior phonological processing relative to reading-level matched children.

The Relationship Between Temporal Processing and Phonological Processing

The comparison of dyslexic adults to chronological-age matched and reading-level matched controls is not the only source of evidence refuting the temporal processing deficit hypothesis. Three sources of evidence that contradict the timing hypothesis are revealed via the examination of the relationships among the reading, phonological processing, and timing variables.

The first source of evidence undermining the existence of a class of hypothesized timing mechanisms is derived from the correlational analyses. Proponents of the temporal processing deficit hypothesis have proposed that reading failure is the result of an impaired timing mechanism (e.g., Farmer & Klein, 1995; Wolff et al., 1990a, 1990b). This mechanism is believed to be involved in the temporal organization of perception and/or action. Two scenarios would support the existence of such a mechanism. On the one hand, if a domain-specific timing mechanism is involved, one would expect performance on experimental timing tasks to be correlated with each other within the different modalities. On the other hand, if a domain-general timing mechanism exists, one would expect performance on experimental timing tasks to be correlated with each other across domains, as well as within modalities. However, performance on the experimental timing tasks tended to correlate poorly with one another, even within domains. For example, the measures from syllable repetition tended to produce low correlations with naming speed (r = .30), and tapping was uncorrelated with simultaneously placing pennies in a box and drawing lines and crosses. On many of these tasks, dyslexic adults performed significantly worse than chronological-age controls. Because these tasks were sensitive enough to discriminate between skilled and less-skilled readers, the failure to find correlations among the tasks cannot be attributed to lack of sufficient power. Therefore, the absence of robust correlations between the experimental timing measures within domains may be interpreted as evidence against the involvement of a defective timing mechanism.

The one domain in which there were moderate correlations among the experimental timing tasks was the domain of perception. Low to moderate correlations were revealed between the two gap detection tasks and the Seashore Rhythm test. However, the correlations between the visual and auditory gap detection tasks may be attributed to the fact that minor variations to the same paradigm was used for these tasks. The Seashore Rhythm test, however, correlated moderately with both auditory and visual gap detection. The Seashore Rhythm test requires individuals to make judgments of temporal order, which is dependent on the ability to discriminate between long and short stimuli. That is, the perception of temporal order requires that the successively presented stimuli are first identified accurately (Hirsh & Sherrick, 1961). If an individual has difficulty discriminating between long and short stimuli, which may be manifested as impaired performance on the gap detection tasks, that individual will experience difficulties recognizing the temporal order in which those hard-to-discriminate stimuli were presented. Note that there is no need to invoke an underlying timing mechanism as the causal factor underlying performance on the gap detection and Seashore Rhythm tests in order to explain the correlations between the tasks. One can parsimoniously explain the correlation between the tasks using perceptual skill as the limiting factor. Therefore, the moderate correlations between the experimental tasks testing perception may be attributed to similarities between the tasks or perceptual deficits, and not necessarily to an underlying timing mechanism.

As an interesting aside, the timing tasks tended to correlate much better with reading and phonological measures than they did with each other. This is consonant with the findings of several similar studies that the timing tasks were correlated with word reading (Wolf, Bally & Morris, 1986; Wolff et al., 1990; Zurif & Carson, 1970), reading comprehension (Bowers, Steffy

& Tate, 1988; Wolf & Obregon, 1992), pseudoword reading (Bowers & Swanson, 1991; Tallal, 1980) and phoneme segmentation (Bowers & Swanson, 1991). Although it is intriguing to note the correlations between performance on the experimental timing tasks and the academic measures, it is important not to overinterpret them. Due to the low correlations among the experimental tasks, one cannot claim that their moderate correlations with the academic measures is evidence that impaired temporal processing results in low academic achievement. A viable alternative explanation for these correlations is that a variety of fairly generic factors, such as the individuals' speed of processing, motivation, ability to attend to the tasks, and skill at following directions influence their performance on both the experimental timing tasks and the academic measures. These factors tend to enhance performance in a variety of cognitive domains, and their influence is not restricted to reading skill.

While the correlational analyses showed that performance on the experimental timing variables is not influenced by a common underlying timing mechanism, the regression analyses provided a second source of evidence against the temporal processing hypothesis. Four regression analyses using different measures of word reading as criterion variables produced the same pattern of results. The only experimental timing variable that contributed variance independent of phonological processing in word reading skill was continuous naming speed. Despite the fact that other experimental timing variables, such as latency in auditory gap detection and syllable repetition, correlated with word reading skill as well as continuous naming speed, these other measures failed to contribute additional variance in word recognition. In fact, continuous naming speed proved to be such a robust predictor of reading skill, it also proved to be the sole predictor of spelling and print exposure measures independent of phonological processing. The current replication of continuous RAN's ability to predict reading skill is consistent with a growing number of studies (e.g., Badian, 1993; Badian, McAnulty, Duffy & Als, 1990; Bowers & Swanson, 1991; Wolf, 1991a; Wolf & Obregon, 1992).

Continuous naming speed deficits have often been attributed to underlying temporal processing deficits (e.g. Wolff et al., 1990a). For example, authors such as Wolf (1991a) have suggested the possibility that reading failure might result from "a general propensity towards a slower functioning in linguistic and possibly motor functions, based on the failure of an underlying temporal processing mechanism" (p.138). However, it is more probable that continuous naming speed deficits reflect a linguistic deficit, rather than a temporal processing deficit. For example, a stepwise regression analysis was conducted in order to determine which measures were predictive of continuous naming speed. The predictor variables included estimated IQ, measures of word reading skill, phonological processing, orthographic processing, and all the experimental timing measures. The two significant predictors of continuous naming speed were skill at word reading, and performance on the discrete-trial RAN. The failure to find a single experimental timing measure (that was not a variation of the RAN paradigm) contributing variance in continuous naming speed suggests that a word-retrieval deficit, and not a temporal processing deficit, may be implicated in continuous naming deficits. If word retrieval deficits are the cause of slow naming speeds (Badian, 1993), than the variance explained by the continuous RAN in reading skill must be attributed to deficient linguistic processing and not to temporal processing deficits.

Finally, the relationship between phonological processing, naming speed, and performance on the remaining experimental timing tasks was explored with commonality analyses. The four commonality analyses using WRAT3 reading as the criterion variable produced the same pattern of results. Although continuous naming speed and skill at phoneme segmentation tended to share approximately 20% of the variance, both measures also contributed variance independent of each other. In contrast, the timing measures contributed very little unique variance in word reading skill. Furthermore, three of the timing measures shared little variance (range 1.3 to 9.2%) with phoneme segmentation skill and continuous naming speed. This is true even of the Timing-Best variable, which was constructed in a manner intended to maximize the possibility of contributing variance to word recognition. The inclusion of the three variables with the highest zero-order correlations with word reading skill in the Timing-Best variable was meant to maximize this variable's relationship with word reading. These results clearly indicate that temporal processing deficits cannot be implicated either directly or indirectly in reading failure. Because performance on the experimental timing tasks shared negligible variance with the Rosner AAT, it is unreasonable to believe that temporal processing deficits underlie phonological processing deficits. Similarly, it is very unlikely that deficits in continuous naming speed result from impaired temporal processing because it too shared very little variance with timing measures. Because of the large amount of variance shared with phonological processing, it is likely that RAN performance is largely phonological in nature.

In short, there was little support for any version of the temporal processing deficit hypothesis. The absence of significant group by ISI interactions, the lack of robust correlations between timing tasks, and the failure of the timing variables to explain unique variance in word reading skill converged to undermine the timing deficit hypothesis. Similarly, the timing variables shared little variance with phonemic awareness. Therefore, an impaired timing mechanism cannot be used as a causal explanation for the phonological deficit that characterizes reading failure.

Theoretical Inferences

Although dyslexics in general performed more poorly than normal readers, the pattern of results (*i.e.*, the absence of group by rate interactions) undermined the temporal processing deficit hypothesis of developmental dyslexia. Although the experimental tasks were sensitive enough to reveal group differences between disabled and nondisabled readers, the main prediction of the timing hypothesis, that disabled readers will be impaired on tasks with rapid but not slow processing demands, was not confirmed. Because performance on the experimental timing measures was uncorrelated with each other, the evidence refuted the possibility of a shared underlying construct (a timing mechanism). Finally, with the exception of continuous naming speed, the experimental timing measures failed to be predictive of a variety of reading measures. In fact, the experimental timing measures shared very little variance with phonological processing, rendering it extremely unlikely that temporal processing underlies the phonological core deficit of reading disability.

Although the findings of this thesis undermine all variations of the temporal processing deficit hypothesis, they also suggest a potentially more promising hypothesis in the understanding of reading disability. This hypothesis is that word retrieval deficits are involved in reading disability. The finding that adult dyslexics name lists of digits more slowly than normal readers, and that this impairment is a reliable predictor of reading skill independent of phonological processing, is consonant with the findings of similar studies (e.g. Badian, 1993; Badian, McAnulty, Duffy & Als, 1990; Bowers & Swanson, 1991; Felton & Brown, 1990; Korhonen, 1995; Wolf, 1991a; Wolf & Obregon, 1992; Wolff et al., 1990a). In fact, even before reading is acquired, deficits in naming speed can be used to successfully identify impairments in processes that would later be involved in reading development (Wolf, 1991b). Therefore, impairments in the word-retrieval, or naming system is a likelier cause of reading failure than impaired temporal processing. However, the current study was not designed to conclusively determine whether or not the word retrieval deficit is linked to the phonological deficits that underlie phonemic awareness. That is, it is not clear whether the slow naming rate may be used as an index of a general phonological deficit, or if it reflects a construct that is separate from phonemic awareness.

Mechanisms that are among the best candidates as key processing mechanisms that underlie reading disability would be modular systems (Stanovich, 1986a, 1988). Modular systems refer to those that are fast, automatic, and informationally encapsulated (Fodor, 1983). These systems are not under the control of higher level structures, and the failure of modular systems do not disrupt unrelated central cognitive processes, or cognitive processes that are not dependent on the modular system's output. Reading disability can occur in the presence or absence of central cognitive impairments. For example, the phonological processing deficits that characterize developmental dyslexia are observed in disabled readers with both high and low IQs (Siegel, 1988, 1989). For a mechanism to be a plausible cause of reading disability, it must be specific to poor reading performance and not cause general cognitive impairment. If a mechanism causes general cognitive impairment, than it would be impossible for there to be dyslexics with high IQs. However, there clearly exist dyslexics with high IQs (Siegel, 1988, 1989). Therefore, a processing system that respects the conditions of modularity is a viable candidates as the mechanism which underlies reading disability.

One such candidate is word retrieval. While word retrieval or naming satisfies many of the conditions of modular systems, its ability to account for unique variance in word reading skill suggest that it may be involved in reading disability. Wolf (1991b) has argued that the rapid integration of visual, semantic, and phonological processes in word retrieval, and the relative dissociation of naming from IQ suggests that lexical access is a modularized process. Corroboration of word retrieval's independence of other cognitive processes was provided by the current study. Stepwise regression analyses revealed that serial naming speed (as indicated by the discrete-trial RAN) and word reading were the only variables that shared significant variance with continuous naming speed. Measures such as IQ or the experimental timing measures did not share significant variance with continuous naming speed. Therefore, although the construct of naming speed is independent of other cognitive processes, the subprocesses involved in the retrieval of verbal labels are involved with the subprocesses used to retrieve words when reading. It therefore appears that naming speed deficits reflect one area that is specific to developmental dyslexia, in addition to phonological processing deficits. These findings provide a very tentative argument against phonological processing representing a single construct. That is, although a great deal of variance was shared between naming speed and phonemic segmentation, naming speed did have some unique variance. This suggests that word retrieval has some independence from phonological awareness.

While dyslexic adults display continuous naming speed deficits, one must determine whether this deficit reflects phonological problems (Katz, 1986), inadequately stored semantic information (Kail & Leonard cited in Wolf & Obregon, 1992), or a general oral language deficit (Murphy, Pollatsek & Well, 1988). The findings of the current study suggest that naming speed deficits may reflect difficulties in phonological processing. Recall that approximately two-thirds of the variance that naming speed contributed to reading skill was shared with phoneme segmentation. In other words, only one-third of the variance naming speed contributed to word reading was independent of phonemic awareness. This means that although the two measures diverge, an underlying construct is involved in both phoneme segmentation and naming. The common construct is very likely a general skill at phonological processing. However, the divergence between the two tasks reflects two different classes of skills involved in phonological processing, phonological awareness and name retrieval (what Wagner & Torgesen, 1987 call phonological recoding in lexical access). Phonological awareness refers to the ability to identify and manipulate phonemes, and is often assessed using phoneme segmentation tasks such as the Rosner AAT. While phonological awareness reflects receptive skills, phonological recoding in lexical access, which is frequently assessed using the RAN paradigm (Badian, 1993), involves production abilities. Therefore, although rapid naming deficits likely reflect problems in phonological processing, they contribute additional variance in word reading beyond the influence of phonological awareness tasks because they involve the retrieval of phonological representations prior to output processes. This is not surprising because the subprocesses involved in lexical access in naming are also implicated in lexical access in word reading.

Although the discrete trial RAN was one of the two variables that were predictive of continuous naming speed, it did not account for unique variance in word reading. In fact, serial naming speed discriminated between normal and disabled readers when the ISI was long, but not when it was short. These findings reflect the inconsistency with which discrete trial RAN has been predictive of reading skill. For example, Stanovich and his colleagues (Stanovich, 1981; Stanovich, Feeman & Cunningham, 1983; Stanovich, Nathan & Zolman, 1988) found that children's latencies for correct responses in the discrete-trial RAN did not always correlate significantly with reading skill. In fact, Stanovich et al. (1988) found that discrete-trial naming speed correlated better with age than reading skill! This led the authors to conclude that discrete-trial naming is not an important contributor to reading skill. Similarly, Perfetti, Finger and Hogaboam (1978) also found that discrete-trial RAN was not discriminative of skilled and unskilled reading. In contrast, other studies have reported that discrete-trial latencies successfully discriminated between normal and disabled readers (e.g., Bowers & Swanson, 1991; Ehri & Wilce, 1983; Levy & Hinchley, 1990; Yap & Van der Leij, 1993). For example, Ehri & Wilce (1983) reported that discrete-trial latencies discriminated between skilled and less-skilled readers in grades 1, 2 and 4. In order to better understand continuous naming speed's relationship with reading skill, one must investigate its relationship with discrete-trial naming speed.

Although both tasks involve word retrieval, it is believed that the continuous and discrete-trial formats of the RAN task involve different cognitive processes. Reading may have more cognitive processes in common with the continuous version of the naming task. These processes include word retrieval within the context of rapid scanning, sequencing and processing of contiguous material (Wolf, 1991a). In contrast, the discrete-trial RAN may be considered a purer measure of word-retrieval speed (Stanovich, 1988; Wolf, 1991a). Extraneous sources of variance, such as speed in scanning and sequencing, have been removed from the task requirements. Therefore, contradictory findings between the continuous and discrete-trial naming tasks, such as those from the present study, are not theoretically problematic. Rather, they indicate the context in which lexical access becomes problematic for disabled readers. The discrimination of disabled readers from normal readers in the continuous naming task, but not necessarily in the discrete-trial naming task suggests that lexical access becomes problematic when more subprocesses must be integrated. This pattern is analogous to the finding that Stroop interference is dramatically reduced when stimuli are presented serially rather than in a continuous list (Dalrymple-Alford & Budayr, 1966; Neill, 1977). Therefore, the different patterns of performance produced by the continuous and discrete-trial versions of the RAN task is informative of the context in which naming deficits arise.

Finally, continuous-list naming speeds may be more predictive of reading skill than discrete trial measures as a result of structural and psychometric differences in the tasks. In the continuous RAN, the latency score is the total time necessary for an individual to name all the items in a set of visual stimuli including errors. The errors are considered process-indicative because they reflect disruptions in the word retrieval process (Rudel in Wolf, 1991a). In contrast, the latency score of the discrete-trial RAN reflects the average time required for an individual to name a single stimulus presented tachistoscopically. Thus, outliers and errors are removed from the analyses (Bowers, Golden, Kennedy & Young, 1995). The removal of errors from the analyses in discrete-trial naming would likely have the effect of diminishing differences between disabled and nondisabled readers. Therefore, although discrete-trial RAN may be considered a purer measure of word retrieval than continuous naming, the removal of errors and outliers from the analyses also results in the removal of information that is indicative of disruptions in lexical access.

Summary and Future Directions

The current thesis investigated the hypothesis that the phonological deficit associated with reading failure is caused by an impaired timing mechanism. However, the current results clearly indicate that the temporal processing deficit hypothesis of developmental dyslexia cannot provide a causal explanation for reading failure. Despite significant group differences between normal and dyslexic adults on the timing tasks and moderate correlations between timing tasks and word reading skill, key predictions of the timing hypothesis were not observed. Although all variations of the timing hypothesis predict that disabled readers would show impaired performance on tasks that require the rapid processing of stimuli but not on tasks without speeded performance requirements, no group by rate interaction was significant in the predicted direction. Therefore, despite the overall pattern of poor performance by dyslexic adults, the timing hypothesis was unable to explains dyslexics' patterns of impairment.

A second important failure of the timing hypothesis was revealed through the comparison with younger skilled readers matched on reading skill. Dyslexics showed the classic pattern of impairment in the investigation of phonological processing (Bruck & Treiman, 1990; Rack et al., 1992; Stanovich & Siegel, 1994). That is, the younger children outperformed the older disabled readers on a phoneme segmentation task and in pseudoword reading. This is consistent with the phenotypic performance profile of dyslexia. However, the dyslexics performed at least as well, if not better, than the reading-level matched children, revealing no evidence of a temporal processing deficit relative to reading-level matched controls. Because there was no evidence of a specific timing deficit, it cannot be used as a causal explanation for dyslexics' inferior phonological processing relative to reading-level matched children

Finally, with the exception of naming speed, the timing tasks failed to explain unique variance in word reading. Because the commonality analyses revealed that naming speed shared very little variance with the timing variables, it is unlikely that naming speed reflects a construct that is independent of temporal processing. Rather, deficits in word retrieval, and not temporal processing, play an important role in reading failure. The impairment in lexical access seems to reflect phonological problems, and not timing deficits. Therefore, further research in the attempt to gain a better understanding of word retrieval and its role in reading disability is urged.

The relationship between word retrieval and phonological processing is deserving of further investigation. Although phonological awareness (as measured by the Rosner AAT) was the most potent predictor of word reading skill, naming speed contributed additional unique variance. This suggests that word retrieval has some independence from phonological awareness. However, a great deal of variance was shared between naming speed and phoneme segmentation, suggesting a common construct is involved in word retrieval and phonological awareness. Therefore, the role of word retrieval in reading skill, relative to phonological awareness requires further investigation. Research of particular importance would be the determination of the locus of divergence between phonological awareness and word retrieval, which may address the roles of prelexical and postlexical processing in phonological awareness and naming tasks.

A second issue worthy of investigation is the determination of the underlying cause of slow word retrieval rates. This goal might be achieved through a microanalysis of RAN performance. Such an investigation would explore the relationship between articulation rate, accuracy in word retrieval and naming speed. Particular attention would be devoted towards the analysis of corrected errors in naming speed. Such an investigation would reveal whether slow naming speeds reflect slower processing in lexical access, or less accurate processing. Because the results of the current thesis suggest that disabled readers do not show impaired temporal processing, it is likely that naming speed deficits revealed by the continuous version of RAN result from impairments in the selection of the correct lexical candidate.

In conclusion, the findings of the current thesis undermine all versions of the timing hypothesis as a causal explanation for reading failure. However, in addition to measures of phonological awareness, naming speed deficits proved to be a robust predictor of word reading skill. Because naming speed proved to be independent of other timing tasks, it is more likely a reflection of word retrieval impairments. However, further investigation is required to determine the underlying cause of word retrieval deficits and its role in reading failure.

References

Ackerman, P. T., Dykman, R. A., & Gardner, M. Y. (1990). Counting rate, naming rate, phonological sensitivity, and memory span: Major factors in dyslexia. Journal of Learning Disabilities, 23, 325-327, 319.

Adams, M. J. (1990). Beginning to read: Thinking and learning about print. Cambridge, MA: MIT Press.

Arnett, M., & Di Lollo, V. (1979). Visual information processing in relation to age and reading ability. Journal of Experimental Child Psychology, 27, 143-152.

Badcock, D., & Lovegrove, W. (1981). The effects of contrast, stimulus duration, and spatial frequency on visible persistence in normal and specifically disabled readers. Journal of Experimental Psychology: Human Perception and Performance, 7, 495-505.

Badian, N. A. (1993). Phonemic awareness, naming, visual symbol processing, and reading. Reading and Writing: An Interdisciplinary Journal, 5, 87-100.

Badian, N. A., McAnulty, G. B., Duffy, F. H., & Als, H. (1990). Prediction of dyslexia in kindergarten boys. Annals of Dyslexia, 40, 152-169.

Badian, N. A., & Wolff, P. H. (1977). Manual asymmetries of motor sequencing in boys with reading disability. Cortex, 13, 343-349.

Barker, K., Torgesen, J. K., & Wagner, R. K. (1992). The role of orthographic processing skills on five different reading tasks. Reading Research Quarterly, 27, 334-345.

Beauvois, M. F., & Derouesne, J. (1979). Phonological alexia: Three dissociations. Journal of Neurology, Neurosurgery & Psychiatry, 42, 1115-1124.

Behrmann, M., & Bub, D. (1992). Surface dyslexia and dysgraphia: Dual routes, single lexicon. Cognitive Neuropsychology, 9, 209-251.

Bentin, S. (1992). Phonological awareness, reading and reading acquisition. In R. Frost & L. Katz (Eds.), Orthography, phonology, morphology, and meaning. Amsterdam: North-Holland. Pp. 193-210.

Benton, A. L. (1955). Development of finger-localization capacity in school children. Child Development, 26, 225-230.

Berndt, R., Reggia, J., & Mitchum, C. (1987). Empirically derived probabilities for grapheme-to-phoneme correspondences in English. Behavior Research Methods, Instruments, & Computers, 19, 1-9.

Boder, E. (1973). Developmental dyslexia: A diagnostic approach based on three typical reading-spelling patterns. Developmental Medicine and Child Neurology, 15, 663-687.

Bowers, P. G. (1995). Tracing symbol naming speed's unique contributions to reading disabilities over time. Reading and Writing: An Interdisciplinary Journal, 7, 189-216.

Bowers, P. G., Golden, J., Kennedy, A., & Young, A. (1995). Limits upon orthographic knowledge due to processes indexed by naming speed. In V. W. Berninger (Ed.), The varieties of orthographic knowledge (Vol. 1). Dordrecht, The Netherlands: Kluwer Academic. Pp. 173-218.

Bowers, P. G., Steffy, R., & Tate, E. (1988). Comparison of the effects of IQ control methods on memory and naming speed predictors of reading disability. Reading Research Quarterly, 23, 304-319.

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: Multiple measures of a singular process. Journal of Experimental Child Psychology, 51, 195-219.

Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. Reading and Writing: An Interdisciplinary Journal, 5, 69-85.

Bowey, J. A., Cain, M. T., & Ryan, S. M. (1992). A reading-level design study of phonological skills underlying fourth-grade children's word reading difficulties. Child Development, 63, 999-1011.

Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read - a causal connection. *Nature, 601*, 119-121.

Brown, J. I., Nelson, M. J., & Denny, E. C. (1973). *The Nelson-Denny reading test.* Boston, MA: Houghton Mifflin Co.

Bruck, M. (1988). The word recognition and spelling of dyslexic children. *Reading Research Quarterly*, *23*, 51-69.

Bruck, M. (1990). Word-recognition skills of adults with childhood diagnoses of dyslexia. *Developmental Psychology*, *26*, 439-454.

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology*, *28*, 874-886.

Bruck, M. & Treiman, R. (1990). Phonological awareness and spelling in normal children and dyslexics: The case of initial consonant clusters. *Journal of Experimental Child Psychology*, *50*, 156-178.

Bruininks, R. H. (1978). *Bruininks-Oseretsky Test of Motor Proficiency*. Circle Pines, MN: American Guidance Service.

Bryant, P. E., Bradley, L., MacLean, M., & Crossland, J. (1989). Nursery rhymes, phonological skills, and reading. *Journal of Child Language*, *16*, 407-428.

Bryant, P. & Goswami, U. (1986). Strengths and wesknesses of the reading level design: A comment on Backman, Mamen, and Ferguson. *Psychological Bulletin*, *100*, 101-103.

Bryant, P., & Impey, L. (1986). The similarities between normal readers and developmental and acquired dyslexics. *Cognition*, *24*, 121-137.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, *47*, 149-180.

Catts, H. W. (1991). Early identification of reading disabilities. Topics in Language Disorders, 12(1), 1-16.

Chiappe, P., Stanovich, K. E., & Siegel, L. S. (1996). Regularity and consistency in word recognition: A comparison between dyslexics and normal readers. Paper presented at the annual meeting of the American Educational Research Association, New York.

Coltheart, M. (1980). Iconic memory and visible persistence. Perception and Psychophysics, 27, 183-228.

Coltheart, M., Masterson, J., Byng, S., Prior, M., & Riddoch, J. (1983). Surface dyslexia. Quarterly Journal of Experimental Psychology, 37A, 469-495.

Coltheart, V., & Leahy, J. (1992). Children's and adults' reading of nonwords: Effects of regularity and consistency. Journal of Experimental Psychology: Learning Memory, and Cognition, 18, 718-729.

Corso, J. F. (1963). A theoretico-historical review of the threshold concept. Psychological Bulletin, 60, 356-370.

Cunningham, A. E. (1990). Explicit versus implicit instruction in phonemic awareness. Journal of Experimental Child Psychology, 50, 429-444.

Dalrymple-Alford, E. C., & Budayr, B. (1966). Examination of some aspects of Stroop colour-word test. Perceptual and Motor Skills, 23, 1211-1214.

Das, J. P., Mishra, R. K., & Kirby, J. R. (1994). Cognitive patterns of children with dyslexia: A comparison between groups with high and average nonverbal intelligence. Journal of Learning Disabilities, 27, 235-242, 253.

Denckla, M. B. (1972). Colour naming defects in dyslexic boys. Cortex, 8, 164-176.

Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (R.A.N.): Dyslexia differentiated from other learning disabilities. Neuropsychologia, 14, 474-479.

Carroll, J. B., Davies, P., & Richman, B. (1971). Word frequency book. Boston: Houghton Mifflin.

Di Lollo, B., Hanson, D., & McIntyre, J. S. (1983). Initial stages of visual information processing in dyslexia. Journal of Experimental Psychology: Human Perception and Performance, 9, 923-935.

Ehri, L. (1985). Effects of printed language acquisition on speech. In D. Olson, N. Torrance, & A. Hildyard (Eds.), Literacy, language, and learning. New York: Cambridge University Press. Pp. 333-367.

Ehri, L., & Wilce, L. (1983). Development of word identification speed in skilled and less skilled beginning readers. Journal of Educational Psychology, 75, 3-18.

Ehri, L., & Wilce, L. (1985). Movement into reading: Is the first stage of printed word learning visual or phonetic? Reading Research Quarterly, 20, 163-179.

Farmer, M. E., & Klein, R. M. (1993). Auditory and visual temporal processing in dyslexic and normal readers. Annals of the New York Academy of Sciences, 682, 339-341.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. Psychonomic Bulletin & Review, 2, 460-493.

Fawcett, A. J., & Nicolson, R. I. (1992). Automatisation deficits in balance for dyslexic children. Perceptual Motor Skills, 75, 507-529.

Fawcett, A. J., & Nicolson, R. I. (1994). Naming speed in children with dyslexia. Journal of Learning Disabilities, 27, 641-646.

Felton, R. H. & Brown, I. S. (1990). Phonological processes as predictors of specific reading skills in children at risk for reading failure. Reading and Writing: An Interdisciplinary Journal, 2, 39-59.

Felton, R. H., & Wood, F. B. (1992). A reading level match study of nonword reading skills in poor readers with varying IQ. Journal of Learning Disabilities, 25, 318-326.

Fletcher, J. M., Francis, D. J., Rourke, B. P., Shaywitz, B. A., & Shaywitz, S. E. (1992). The validity of discrepancy-based definitions of reading disabilities. Journal of Learning Disabilities, 25, 555-561.

Fletcher, J. M., Shaywitz, S. E., Shankweiler, D. P., Katz, L., Liberman, I. Y., Steubing, K. K., Francis, D. J., Fowler, A. E., & Shaywitz, B. A. (1992). Cognitive profiles of reading disability: Comparisons of discrepancy and low achievement definitions. Journal of Educational Psychology, 86, 6-23.

Fodor, J. A. (1983). Modularity of mind. Cambridge, MA: MIT Press.

Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. In S. A. Brady & D. P. Shankweiler (Eds.), Phonological processes in literacy. Hillsdale, NJ: Erlbaum. Pp. 97-117.

Gathercole, S. E., & Baddeley, A. D. (1987). The process underlying segmental analysis. European Bulletin of Cognitive Psychology, 7, 462-464.

Glushko, R. (1979). The organization and activation of orthographic knowledge in reading aloud. Journal of Experimental Psychology: Human Perception and Performance, 5, 674-691.

Goswami, U., & Bryant, P. E. (1990). Phonological skills and learning to read. Hillsdale, NJ: Erlbaum.

Halstead, W. C. (1947). Brain and Intelligence. Chicago: University of Chicago Press.

Hirsh, I. J., & Sherrick, C. E. Jr. (1961). Perceived order in different sense modalities. Journal of Experimental Psychology, 62, 423-432.

Høien, T., Lundberg, I., Stanovich, K. E., & Bjaalid, I. K. (1995). Components of phonological awareness. Reading and Writing: An Interdisciplinary Journal, 7, 171-188.

Hulme, C. (1988). The implausibility of low-level visual deficits as a cause of children's reading difficulties. Cognitive Neuropsychology, 5, 369-374.

Hynd, G. S., Marshall, R., & Gonzalez, J. (1991). Learning disabilities and presumed central nervous system dysfunction. Learning Disability Quarterly, 14, 283-296.

Jorm, A. G., & Share, D. L. (1983). Phonological recoding and reading acquisition. Applied Psycholinguistics, 4, 103-147.

Katz, R. B. (1986). Phonological deficiencies in children with reading disability: Evidence from an object naming task. Cognition, 22, 225-257.

Katz, W. F., Curtiss, S., & Tallal, P. (1992). Rapid automatized naming and gesture by normal and language-impaired children. Brain and Language, 43, 634-641.

Kerlinger, F. N., & Pedhazur, E. J. (1973). Multiple regression in behavioral research. New York: Holt, Rinehart and Winston.

Klicpera, C., Wolff, P. H., & Drake, C. (1981). Bimanual co-ordination in adolescent boys with reading retardation. Developmental Medicine and Child Neurology, 23, 617-625.

Korhonen, T. T. (1995). The persistence of rapid naming problems in children with reading disabilities: A nine-year follow-up. Journal of Learning Disabilities, 28, 232-239.

Kruk, R. (1991). Functional consequences of a transient visual processing deficit in reading disabled children. Unpublished doctoral dissertation. Ontario Institute for Studies in Eduction, Toronto.

Larsen, P. Høien, T., Lundberg, I., & Odegaard, H. (1990). MRI evaluation of the size and symmetry of the planum temporale in adolsecents with developmental dyslexia. Brain and Language, 39, 289-301.

Levy, B. A., & Hinchley, J. (1990). Individual and developmental differences in the acquisition of reading skills. In T. H. Carr & B. A. Levy (Eds.), Reading and its development: component skills approaches. New York: Academic Press. Pp. 81-128.

Liberman, I. Y., Shankweiler, D., Fisher, F. W., & Carter, B. (1974). Explicit syllable and phoneme segmentation in the young child. Journal of Experimental Child Psychology, 18, 201-212.

Lovegrove, W. J., Heddle, M., & Slaghuis, W. (1980). Reading disability: Spatial frequency specific deficits in visual information store. Neuropsychologia, 18, 111-115.

Lovegrove, W. J., Martin, F., & Slaghuis, W. (1986). A theoretical and experimental case for a visual deficit in specific reading disability. Cognitive Neuropsychology, 3, 225-267.

Lovegrove, W. J., Slaghuis, W., Bowling, A., Nelson, P., & Geeves, E. (1986). Spatial frequency processing and the prediction of reading ability: A preliminary investigation. Perception and Psychophysics, 40, 440-444.

Lundberg, I., Frost, J., & Peterson, O. (1988). Effects of an extensive program for stimulating phonological awareness in preschool children. Reading Research Quarterly, 23, 263-284.

MacMillan, N. A., & Creelman, C. D. (1991). Detection theory: A user's guide. New York: Cambridge University Press.

Manis, F. R., Custudio, R., & Szeszulski, P. A. Development of phonological and orthographic skill: A 2-year longitudinal study of dyslexic children. Journal of Experimental Child Psychology, 56, 64-86.

Manis, F. R., Seidenberg, M. S., Doi, L., McBride-Chang, C., & Petersen, A. (in press). On the basis of two subtypes of developmental dyslexia. Cognition.

Mann, V. (1984). Reading skill and language skill. Developmental Review, 4, 1-15.

Mazer, S. R., McIntyre, C. W., Murray, M. E., Till, R. E., & Blackwell, S. L. (1983). Visual persistence and information pick-up in learning disabled children. Journal of Learning Disabilities, 16, 221-225, 240.

McBride-Chang, C., & Manis, F. R. (1996). Structural invariance in the associations of naming speed, phonological awareness, and verbal reasoning in good and poor readers: A test of the double deficit hypothesis. Reading and Writing: An Interdisciplinary Journal, 8, 323-339.

McCroskey, R. L., & Kidder, H. C. (1980). Auditory fusion among learning disabled, reading disabled, and normal children. Journal of Learning Disabilities, 13, 18-25.

McGivern, R. F., Berka, C., Languis, M. L., & Chapman, S. (1991). Detection of deficits in temporal pattern discrimination using the Seashore Rhythm Test in young children with reading impairments. Journal of Learning Disabilities, 13, 58-62.

Mody, M., Studdert-Kennedy, M., & Brady, S. (in press). Speech perception deficits in poor readers: Auditory processing or phonological coding? Journal of Experimental Child Psychology.

Morais, J., Bertelson, P., Cary, L., & Alegria, J. (1979). Does awareness of speech as a sequence of phones arise spontaneously? Cognition, 7, 323-331.

Morrison, F., Giordani, B., & Nagy, J. (1977). Reading disability: An information processing analysis. Science, 196, 77-79.

Murphy, L. A., Pollatsek, A., & Well, A. D. (1988). Developmental dyslexia and word retrieval deficits. Brain and Language, 35, 1-23.

Neill, W. T. (1977). Inhibition and facilitation processes in selective attention. Journal of Experimental Psychology: Human Perception and Performance, 3, 444-450.

Nicolson, R. I., & Fawcett, A. J. (1990). Automaticity: A new frameword for dyslexia research? Cognition, 35, 159-182.

O'Neill, G., & Stanley, G. (1976). Visual processing of straight lines in dyslexic and normal children. British Journal of Educational Psychology, 46, 323-327.

Olson, R. K., Kliegl, R., Davidson, B., & Foltz, G. (1985). Individual and developmental differences in reading disability. In G. E. MacKinnon & T. G. Waller (Eds.), Reading research: Advances in theory and practice (Vol. 4). San Diego, CA: Academic Press. Pp. 1-64.

Olson. R., Wise, B., Conners, F., Rack, J., & Fulker, D. (1989). Specific deficits in component reading and language skills: Genetic and environmental influences. Journal of Learning Disabilities, 22, 339-348.

Patterson, K. E., & Morton, J. (1985). From orthography to phonology: An attempt at an old interpretation. In K. Patterson, J. Marshall, & M. Coltheart (Eds.), Surface dyslexia London: Lawrence Erlbaum Associates. Pp. 335-359.

Pennington, B. F., Gilger, J., Olson, R. K., & DeFries, J. C. (1992). The external validity of age- versus IQ-diescrepancy definitions of reading disability: Lessons from a twin study. Journal of Learning Disabilities, 3, 562-573.

Perfetti, C. A. (1984). Reading acquisition and beyond: Decoding includes cognition. American Journal of Education, 92, 40-60.

Perfetti, C. A. (1985). Reading ability. New York: Oxford University Press.

Perfetti, C. A., Finger, E., & Hogaboam, T. (1978). Sources of vocalization latency differences between skilled and less skilled young readers. Journal of Educational Psychology, 71, 730-739.

Rack, J. P., Snowling, M. J. & Olson, R. K. (1992). The nonword reading deficit in developmental dyslexia: A review. Reading Research Quarterly, 27, 28-53.

Rayner, K., & Pollatsek, A. (1989). The psychology of reading. Englewood Cliffs, NJ: Prentice-Hall.

Rayner, K., Pollatsek, A., & Bilsky, A. B. (1995). Can a temporal processing deficit account for dyslexia? Psychonomic Bulletin & Review, 2, 501-507.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. Journal of Experimental Child Psychology, 48, 270-292.

Rosner, J. & Simon, D. P. (1971). The auditory analysis test: An initial report. Journal of Learning Disabilities, 4, 1-15.

Scarborough, H. S. (1990). Very early language deficits in dyslexic children. Child Development, 61, 1728-1743.

Seidenberg, M. S., Waters, G. S., Barnes, M. A., & Tannenhaus, M. K. (1984). When does irregular spelling or pronunciation influence word recognition? Journal of Verbal Learning and Verbal Behavior, 23, 383-404.

Shallice, T., & Warrington, E. K. (1980). Single and multiple component central dyslexic syndromes. In M. Coltheart, K. E. Patterson, & J. C. Marshall (Eds.), Deep Dyslexia. London: Routledge & Kegan Paul. Pp. 119-145.

Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (1984). Sources of individual differences in reading acquisition. Journal of Educational Psychology, 76, 1309-1324.

Sidhu, R. (1995). An exmination of the contstuct validity of reading disability subtypes. Unpublished masters thesis. Ontario Institute for Studies in Education, Toronto.

Siegel, L. S. (1988). Evidence that IQ scores are irrelevant to the definition and analysis of reading disability. Canadian Journal of Psychology, 42, 201-215.

Siegel, L. S. (1989). IQ is irrelevant to the definition of learning disabilities. Journal of Learning Disabilities, 22, 469-479.

Siegel, L. S. (1992). An evaluation of the discrepancy definition of dyslexia. Journal of Learning Disabilities, 25, 618-629.

Siegel, L. S. (1993). The development of reading. In H. W. Reese (Ed.), Advances in child development and behavior (Vol. 24). San Diego: Academic Press. Pp. 63-97.

Siegel, L. S., & Heaven, R. K. (1986). Categorization of learning disabilities. In S. J. Ceci (Ed.), Handbook of cognitive, social, and neuropsychological aspects of learning disabilities (Vol. 1). Dordrecht, The Netherlands: Kluwer Academic. Pp. 71-84.

Siegel, L. S., & Ryan, E. B. (1988). Development of grammatical sensitivity, phonological, and short-term memory skills in normally achieving and learning disabled children. Developmental Psychology, 24, 28-37.

Siegel, L. S., Share, D., & Geva, E. (1995). Evidence for superior orthographic skills in dyslexics. Psychological Science, 6, 250-254.

Snowling, M. J., Stackhouse, J., & Rack, J. P. (1986). Phonological dyslexia and dysgraphia - A developmental analysis. Cognitive Neuropsychology, 3, 309-339.

Snowling, M. J., van Wagtendonk, B., & Stafford, C. (1988). Object-naming deficits in developmental dyslexia. Journal of Research in Reading, 11, 67-85.

Stanley, G. (1975). Two-part stimulus integration and specific reading disability. Perceptual Motor Skills, 41, 873-874.

Stanley, G., & Hall, R. (1973). Short-term visual information processing in dyslexics. Child Development, 44, 841-844.

Stanovich, K. E. (1981). Relationships between word decoding speed, general name-retrieval ability, and reading progress in first-grade children. Journal of Educational Psychology, 73, 809-815.

Stanovich, K. E. (1986a). Cognitive processes and the reading problems of learning disabled children: Evaluating the assumption of specificity. In J. K. Torgesen & B. Wong (Eds.). Psychological and educational perspectives on learning disabilities. San Diego, CA: Academic Press. Pp. 87-131.

Stanovich, K. E. (1986b). Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. Reading Research Quarterly, 21, 360-406.

Stanovich, K. E. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. Journal of Learning Disabilities, 21, 590-604, 612.

Stanovich, K. E. (1991). Discrepancy definitions of reading disability: Has intelligence led us astray? Reading Research Quarterly, 26, 7-29.

Stanovich, K. E., & Cunningham, A. E. (1992). Studying the consequences of literacy within a literate society: The cognitive correlates of print exposure. Memory & Cognition, 20, 51-68.

Stanovich, K. E., Cunningham, A. E., & Cramer, B. B. (1984). Assessing phonological awareness in kindergarten children: Issues of task comparability. Journal of Experimental Child Psychology, 38, 175-190.

Stanovich, K. E., Cunningham, A. E., & Feeman, D. J. (1984). Intelligence, cognitive skills, and early reading progress. Reading Research Quarterly, 19, 278-303.

Stanovich, K. E., Feeman, D. J., & Cunningham, A. E. (1983). The development of the realtion between letter-naming speed and reading ability. Bulletin of the Psychonomic Society, 21, 199-201.

Stanovich, K. E., Nathan, R. G., & Vala-Rossi, M. (1986). Developmental changes in the cognitive correlates of reading ability and the developmental lag hypothesis. Reading Research Quarterly, 21, 267-283.

Stanovich, K. E., Nathan, R. G., & Zolman, J. E. (1988). The developmental lag hypothesis in reading: Longitudinal and matched reading-level comparisons. Child Development, 59, 71-86.

Stanovich, K. E. & Siegel, L. S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. Journal of Educational Psychology, 86, 24-53.

Stanovich, K. E., Siegel, L. S., Gottardo, A., Chiappe, P., & Sidhu, R. (in press). Subtypes of developmental dyslexia: Differences in phonological and orthographic coding. In B. Blachman (Ed.), Cognitive and Linguistic Foundations of Reading Acquisition. Hillsdale, NJ: Erlbaum.

Stanovich, K. E., & West, R. F. (1989). Exposure to print and orthographic processing. Reading Research Quarterly, 24, 402-433.

Steinmetz, H., & Galaburda, A. M. (1991). Planum temporale asymmetry: In-vivo morphometry affords a new perspective for neurobehavioral research. Reading and Writing: An Interdisciplinary Journal, 3, 331-343.

Studdert-Kennedy, M., Liberman, A. M., Brady, S. A., Fowler, A. E., Mody, M. & Shankweiler, D. P. (1994-1995). Lengthened formant transitions are irrelelvant to the improvement of speech and language impairments. Haskins Laboratories Status Report on Speech Research, SR-119/120, 35-38.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading-impaired: A critical review of the evidence. Psychonomic Bulletin & Review, 2, 508-514.

Tabachnick, B. & Fidell, L. (1983). Using multivariate statistics. New York: Harper & Row.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. Brain and Language, 9, 182-198.

Tallal, P. (1984). Temporal or phonetic processing deficit in dyslexia? That is the question. Applied Psycholinguistics, 5, 167-169.

Tallal, P. (1988). Developmental language disorers: Part 1 - Definition. Human Communication Canada, 12, 7-22.

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Rate of nonverbal processing as a function of sensory modality. Neuropsychologia, 11, 389-398.

Tallal, P., & Piercy, M. (1975). Developmental aphasia: The perception of brief vowels and extended stop consonants. Neuropsychologia, 13, 69-74.

Tallal, P., Sainburg, R. L., & Jernigan, T. (1991). The neuropathology of developmental dysphasia: Behavioral, morphological, and physiological evidence for a pervasive temporal processing disorder. Reading and Writing: An Interdisciplinary Journal, 3, 363-377.

Tallal, P., & Stark, R. E. (1982). Perceptual/motor profiles of reading impaired children with or without concomitant oral language deficits. Annals of Dyslexia, 32, 163-176.

Tanner, W. P., & Swets, J. A. (1954). A decision-making theory of visual detection. Psychological Review, 61, 401-409.

Taraban, R., & McLelland, J. L. (1987). Conspiracy effects in word pronunciation. Journal of Memory and Language, 26, 608-631.

Taylor, H. G., Lean, D., & Schwartz, S. (1989). Pseudoword repetition ability in learning-disabled children. Applied Psycholinguistics, 10, 203-219.

Temple, C. M.., & Marshall, J. C. (1983). A case study of developmental phonological dyslxia. British Journal of Psychology, 74, 517-533.

Thompson, G. H. (1920). A new point of view in the interpretation of threhold measurements in psychophysics. Psychological Review, 27, 300-307.

Thorpe, L. A., Tehub, S. E., Morrongiello, B. A., & Bull, D. (1988). Perceptual grouping in infants and preschool children. Developmental Psychology, 24, 484-491.

Trainor, L. J., & Trehub, S. E. (1993). Musical context effects in infants and adults: Key distance. Journal of Experimental Psychology: Human Perception and Performance, 19, 615-626.

Treiman, R., Mullennix, J., Bijeljac-Babic, R., & Richmond-Welty, E. D. (1995). The special role of rimes in the description, use, and acquisition of English orthography. Journal of Experimental Psychology: General, 124, 107-136.

Tunmer, W. E., & Hoover, W. A. (1992). Cognitive and linguistic factors in learning to read. In P. B. Gough, L. C. Ehri & R. Treiman (Eds.), Reading acquisition (pp. 175-214). Hillsdale, NJ: Erlbaum.

Tunmer, W. E., & Nesdale, A. R. (1985). Phonemic segmentation skill and beginning reading. Journal of Educational Psychology, 77, 417-427.

Tzeng, O. J. L., & Wang, W. S. Y. (1984). Search for a common neurocognitive mechanism for language and movements. American Journal of Physiology, 246, R904-R911._

Vandervelden, M. C., & Siegel, L. S. (1995). Phonological recoding and phoneme awareness in early literacy: A developmental approach. Reading Research Quarterly, 30, 854-875.

Vellutino, F., & Scanlon, D. (1987). Phonological coding, phonological awareness, and reading ability: Evidence from a longitudinal and experimental study. Merrill-Palmer Quarterly, 33, 321-363.

Venezky, R. L. (1970). The structure of English orthography. The Hague: Mouton.

Venezky, R. L., & Massaro, D. W. (1987). Orthographic structure and spelling-sound regularity in reading English words. In A. Allport, D. MacKay, W. Prinz, & E. Scheerer (Eds.), Language perception and production. London: Academic Press. Pp. 159-179.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. Psychological Bulletin, 30, 73-87.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Developmment of reading-related phonological processing abilities: New evidence of bi-directional causality from a latent variable longitudinal study. Developmental Psychology, 85, 83-103.

Waters, G. S., & Seidenberg, M. S. (1985). Spelling-sound effects in reading: Time-course and decision criteria. Memory & Cognition, 13, 557-572.

Wechsler, D. (1974). Wechsler intelligence scale for children: Revised. New York: Psychological Corporation.

Wechsler, D. (1981). WAIS-R manual. New York: Psychological Corporation.

Wechsler, D. (1992). Wechsler individual achievement test New York: Psychological Corporation.

Willows, D. M. (1991). Visual processes in learning disabilities. In B. Y. L. Wong (Ed.), Learning about learning disabilities. San Diego, CA: Academic Press. Pp. 163-193.

Willows, D. M., Kruk, R., & Corcos, E. (1993). Are there differences between disabled and normal readers in their processing of visual information? In D. M. Willows, R. S. Kruk, & E. Corcos (Eds.), Visual processes in reading and reading disabilities. Hillsdale, NJ: LEA. Pp. 265-285.

Wolf, M. (1991a). Naming speed and reading: The contribution of the cognitive neurosciences. Reading Research Quarterly, 26, 123-141.

Wolf, M. (1991b). The word-retrieval deficit hypothesis and developmental dyslexia. Learning and Individual Differences, 3, 205-223.

Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes and reading: A longitudinal study in average and impaired readers. Child Development, 57, 988-1005.

Wolf, M. & Obregon, M. (1992). Early naming deficits, developmental dyslexia, and a specific deficit hypothesis. Brain and Language, 42, 219-247.

Wolff, P. H., Michel, G. F., & Ovrut, M. (1990a). Rate variables and automatized naming in developmental dyslexia. Brain and Language, 39, 556-575.

Wolff, P. H., Michel, G. F., & Ovrut, M. (1990b). The timing of syllable repetition in developmental dyslexia. Journal of Speech and Hearing Research, 33, 281-289.

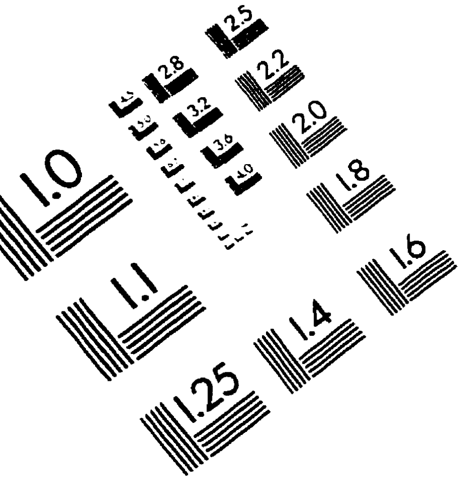
Wolff, P. H., Michel, G. F., Ovrut, M., & Drake, C. (1990). Rate and timing precision of motor coordination in developmental dyslexia. Developmental Psychology, 26, 123-141.

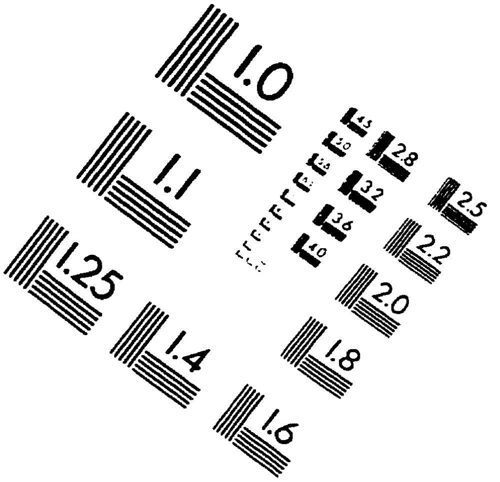
Woodcock, R. W. (1987). Woodcock Reading Mastery Tests - Revised. Circle Pines, MN: American Guidance Service.

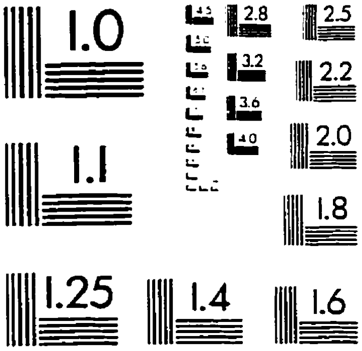
Yap, R. L., & van der Leij, A. (1994). Testing the automatization deficit hypothesis of dyslexia via a dual-task paradigm. Journal of Learning Disabilities, 27, 660-665.

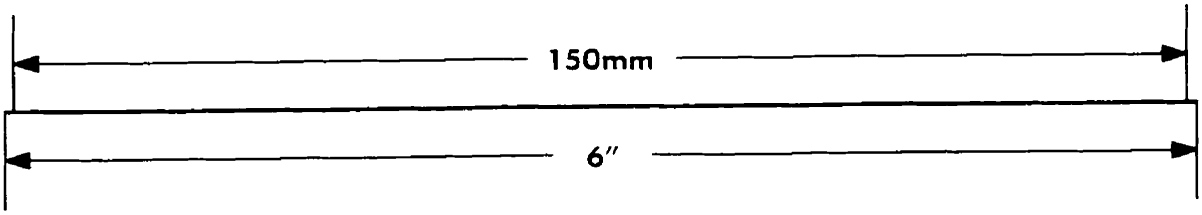
Zurif, E. G., & Carson, G. (1970). Dyslexia in relation to cerebral dominance and temporal analysis. Neuropsychologia, 8, 351-361.

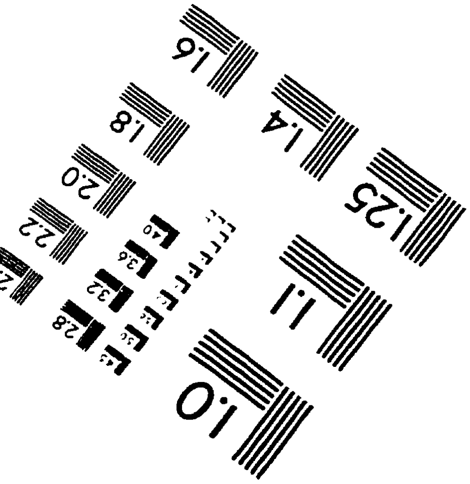
IMAGE EVALUATION TEST TARGET (QA-3)











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