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Motor Control and Reading Fluency: Contributions beyond Phonological Awareness and Rapid Automatized Naming in Children with Reading Disabilities.

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by

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ABSTRACT

Multiple domains of deficit have been proposed to account for the apparent reading failure of children with a reading disability. Deficits in both phonological awareness and rapid automatized naming are consistently linked with the development of a reading disability in young school age children. Less research, however, has sought to connect these two reading related processes to global theories of deficit, such as temporal processing deficits, in the explanation of reading fluency difficulties. This study sought to explore the relationship between aspects of temporal processing, as indexed through measures of motor fluency and control, and measures of reading related processes, phonological awareness and rapid automatized naming, to word reading fluency. Using structural equation modeling, measures of patterned motor movement were found to be negatively and significantly related to measures of phonological awareness. Measures of oral and repetitive movement were found to be positively and significantly related to measures of patterned movement. Finally, phonological awareness was found to be a significant predictor of word reading fluency both independently and through rapid automatized naming. No direct relationship between measures of motor control and fluency and word reading fluency was found. These findings suggest that temporal processing, as indexed by measures of motor fluency and control, are moderately predictive of the facility with which a child with a reading disability can access, manipulate, and reproduce phonetically based information. Implications for the inclusion of motor based measures in the assessment of children with reading disabilities and future directions for research are discussed.

INDEX WORDS: Reading Disability, Phonological Awareness, Rapid Automatized Naming, Motor Fluency, Motor Control

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It is perhaps by virtue of its distinction as a cultural invention that discussions of reading are inherently fraught with definitional problems. The conceptual definition of 'culture' itself has been consistently evaluated and changed depending on the rationale behind and purpose of the investigating researchers. For example, culture can be defined in terms of the practices and customs of a social group (i.e., sociology), by the advent of group dynamics or tool use (i.e., anthropology), or even by the language systems employed by subgroups within an overall population (i.e., sociolinguistics). Given the multiple views that can be brought to bear upon the greater concept of culture, it is no surprise that cultural inventions, such as reading, also can be defined in a variety of ways depending on the theoretical view of the researcher. It is therefore imperative within a discussion of reading to posit the particular view from which the discussion of reading will progress.

The most general understanding of reading builds upon its basic intent: 'Reading is the process of understanding speech written down' (Ziegler & Goswami, 2005). While simple in its description, this basic understanding of reading as a cultural invention for the transcription of oral language into a symbolically mediated visual form represents one of the most important developmental steps for children. Research has found consistently that children achieving below the average level of reading expected either by age or grade level are frequently unable to reach their potential in vocational and/or occupational arenas (Lyon, 1994). Further, children experiencing difficulties in learning to read are rarely unaware of their difficulties. This awareness and subsequent comparison to children who do not exhibit difficulties learning to read has been found to elicit a significantly negative impact on the development of a child's self-concept and self-esteem (Lyon, 2002). Given the plethora of difficulties experienced by children exhibiting either difficulty or disability in the acquisition of reading, it is essential that as researchers we understand the factors that may underlie both the general progression of reading development and those areas in which difficulty or disability may signal future development of specific reading disabilities or dyslexia.

Reading Development

Vellutino, Scanlon, and Tanzman (1994) view reading as developing through the interaction between word identification and spoken language comprehension. In the early stages of reading, word identification plays a larger role in reading development in comparison to spoken language comprehension and provides a basis for the development of reading comprehension. Word identification, as conceptualized by Vellutino and colleagues, encompasses three distinct strategies. One strategy is to attach meaning to a whole word and to use that meaning to extract the word name from memory. A second strategy is to attach a name to the word and use the name to extract the meaning of the word from memory. The third strategy states that the child uses the word's letters and associated sounds to retrieve both its name and meaning from memory (Vellutino et al., 1994). These general strategies build upon an underlying conception of association. In other words, the beginning reader must associate written words to their known lexicon of spoken words, must know that each word is comprised of letters, and must understand that each letter represents individual sounds utilized within speech (Vellutino, Fletcher, Snowling, & Scanlon, 2004).

Empirical research has substantiated many of these assumptions. Vellutino et al. (1994) studied a sample of good and poor readers from two age ranges: grades 2nd - 3rd and 6th - 7th. Word identification was found to be the central component of reading for both groups, such that poor word identification skills inhibited the development of reading comprehension.

Hierarchical regression was used to demonstrate that much of the variance in word identification was explained by a child's facility with letters and sounds, i.e., their phonological awareness.

The Role of Phonological Awareness

By far, the most frequently studied concept in the pursuit of identifying the etiology of reading disabilities concerns the development of phonological awareness (Adams, 1990; Stanovich & Siegel, 1994). At its core, phonological awareness refers to the ability to 'crack' the alphabetic principle of English, or the knowledge that specific phonemes are represented by a set of specific symbols. Wagner, Torgesen, Laughon, Simmons and Rashotte (1993) have suggested further that phonological awareness does not exist as a unitary concept, but is rather a conglomeration of three basic processes necessary for the decoding of the alphabetic principle: phonological sensitivity, phonological representation, and speed of lexical access. The utility of phonological awareness in the explanation of the etiology of reading disabilities has been established by multiple researchers with children and adults of different ages (Adams, 1990; Blachman, 1984; Bruck, 1990;1992), from different linguistic backgrounds (Aro &Wimmer, 2003; Durgunoglu, Nagy, & Hancin-Bhatt, 1993), from both a unitary and multifactorial viewpoint (Morris, Stuebing, & Fletcher et al., 1998), and for children with and without intellectual impairments (Vellutino, Scanlon, & Lyon, 2000). Research also has suggested that deficits related to phonological awareness remain highly predictive of poor reading ability across time (Bruck, 1990; 1992, Wagner, Torgesen, & Rashotte, 1994). Studies such as these, however, have not been able to demonstrate significant relationships between improvement in phonological awareness and other areas integral to increased reading performance such as fluency and comprehension (Torgesen, Alexander, & Wagner, 2001).

Ziegler and Goswami (2005) suggest that the utility of phonological awareness in the development of reading is based on the reader's ability to make use of multiple grain sizes within the English language. These researchers suggest that the beginning reader must surmount three basic difficulties for learning to read in English: availability, consistency and granularity. The availability problem suggests that not all phonological units are explicitly available prior to the introduction of reading; beginning readers are not consciously aware of individual phonemes within speech until explicitly trained through orthographic instruction. The consistency problem reflects the nature of the English language in which orthographic units may have multiple pronunciations and phonological units may be represented by multiple orthographic constructions. Finally, the granularity problem reflects the development of reading through effective translation of a large grain size, such as the large phonological units within speech (e.g., target), into a smaller grain size, such as the limited repertoire of twenty-six letters in the English language (e.g., t-a-r-g-e-t). While training a beginning reader as to this transition between phonology and orthography (i.e., increasing phonological awareness) may serve to address the availability problem by explicitly identifying individual phonemes and address the consistency problem through instruction of the irregularities within English, the skilled reader also must be able to rapidly shift between grain sizes (i.e., phonology-small, orthography-large). This ability to rapidly shift or to become automatic in their processing of orthographic units for phonological information may depend on underlying cognitive structures that mediate the development of phonological and orthographic representations within the long-term memory of the reader. If the phonological and orthographic representations are precise and specific, the beginning reader is able to quickly access this information and associate it with the orally or symbolically presented information (Booth, Perfetti, & MacWhinney, 1999).

Precision in these representations, however, may depend on the speed with which the differing grain sizes can be activated and associated (Perfetti, 1992). Stated another way, Adams (1990) has argued that orthographic pattern recognition depends in part on seeing the letters in sufficient temporal contiguity that they become linked and serve to facilitate each other's long-term memory activation. Temporal contiguity, in this sense, is dependent on the overall cognitive speed of the reader. This factor of cognitive speed has rarely been addressed in research investigating the development of phonological awareness, however, and may represent a more fundamental aspect of cognition observable in other areas of development, such as mathematics, that also depends on speed (Kail & Hall, 1994). In sum, phonological awareness does not fully explain all aspects of effective reading development. Instead, phonological awareness may represent an end result of the processing of reading related information by other lower-level cognitive factors.

The Role of Rapid Automatized Naming

The utility of other cognitive factors beyond phonological awareness in the explanation of reading development signals a departure from the view of reading as a wholly linguistic process (Catts, Adolf, Hogan, & Weismer, 2005) to one of reading as a cognitive process encompassing linguistic factors (e.g., Baddeley, Gathercole & Papagano, 1998). As such, the recognition of cognitive speed as a factor in reading development has gained importance in recent years. As stated previously, in a longitudinal analysis of reading predictors, Wagner et al. (1994) identified three related but separable factors. Two of these predictors, phonological sensitivity and phonological representation, were directly predicated upon an examination of phonological skills. The third, speed of lexical access, did share some variance with the composites of phonological sensitivity and phonological representation, but also contributed unique variance in the prediction of second grade word identification from kindergarten measures. Other researchers have suggested that speed of lexical access is better identified as rapid automatized naming and, while acting in conjunction with phonological awareness, represents an integral factor in reading development (Wolf & Bowers, 1999; Wolf & Katzir-Cohen, 2001).

Building upon earlier neurological examples of disassociations between intact ability to name colors but impaired naming ability for numbers and letters (Denckla, 1972; Denckla & Cutting, 1999), Denckla and Rudel (1976a) suggested that some children show a deficit in the ability to associate particular stimuli with a specific name. They suggested that this deficit may play a role in children with reading disabilities as it may indicate a failure to automatize word reading. In order to investigate this hypothesis, Denckla and Rudel (1976b) created a simple serial naming task referred to as Rapid Automatized Naming (RAN). In these tasks, participants are asked to name five stimuli within one particular domain (i.e., colors (Denckla, 1972), objects, letters, and numbers (Denckla & Rudel, 1974) that are randomly repeated, in a serial format, for a total of 50 stimuli. The goal of the task is to name the stimuli as accurately and quickly as possible. Generally, Denckla and Rudel (1976b) found that children with reading disabilities had longer naming latencies than children without learning impairments and longer naming latencies than children with general learning impairments not specific to reading. Wolf, Bally and Morris (1986) investigated the role of naming speed in reading development for 72 children achieving normally in reading and 11 children with impaired reading ability between kindergarten and second grade. Their results indicate that the speed at which children are able to name a variety of serially presented stimuli (i.e., colors, objects, numbers and letters) significantly predicted reading in the second grade. Further, severe deficiencies in naming speed across these stimuli, particularly for graphonumerical stimuli (i.e., numbers and letters), differentiated between children achieving at average levels of reading skill and children with dyslexia.

Denckla and Cutting (1999) suggested that RAN represents a 'microcosm of reading' in which the connections between visual and verbal information are explicitly taxed through a paradigm requiring dual access within time delimited conditions. The overall demand of the RAN task requires that the associations between a particular symbol and its phonological referent be jointly activated in addition to the motor patterns required for articulation. Deficits in this process, as demonstrated by multiple researchers, signals problems for the developing reading system as it may indicate a slowing in the speed with which both phonological and symbolic information can be accessed and associated (Bowers, Sunseth & Golden, 1999; Manis, Doi, & Bhadha, 2000). Deficits in RAN, therefore, may by caused by a disruption of precise timing mechanisms that influences the temporal integration of phonological and visual components of printed words and impairs the readers' ability to detect and represent orthographic patterns (Bowers & Wolf, 1993; Vellutino et al., 2004)

The Dual Contribution of Phonological Awareness and RAN to Reading Development

Bowers and Wolf (1993) have suggested that children with reading disabilities can be characterized as those with phonological deficits only, those with naming speed deficits only, and those exhibiting deficits in both phonological and naming speed domains. In this theory, individuals exhibiting both phonological and naming speed deficits are characterized by a double-deficit and have the most severe reading impairments (Wolf & Bowers, 1999). Evidence for this conceptualization has been found by multiple researchers. Bowers (1995), using cross-sectional data of children from kindergarten to grade 4, replicated the existence of these three groups in addition to a group without deficits. Further, using a more severe reading disabled population, McBride-Chang and Manis (1996) replicated the presence of these deficit groups in a sample of 125 3rd and 4th grade children. Using scores below the 25th percentile on word identification, 51 participants were classified as having dyslexia while 74, scoring above the 50th percentile on word identification, were classified as typically achieving. Phonological awareness was found to be a significant predictor of word reading in both groups. Naming speed was found to be a significant predictor for word reading for children with dyslexia alone. Naming speed was not found to be a significant predictor for children without dyslexia. Conversely, Torgesen, Wagner, and Rashotte (1997) found that both naming speed and phonological awareness were significant predictors of word reading but that the association between rapid naming and word reading did not remain significant outside the early stages of reading. While a recent review of the research into the applicability of the double-deficit hypothesis for all children with dyslexia has demonstrated conflicting evidence (Vukovic & Siegel, 2006), most researchers agree that the presence of deficits within both phonological processing and rapid serial naming can have severe negative consequences for the development of reading.

Part of the process for untangling the multiple findings and clarifying the relationship between rapid naming and reading development depends on explicating the cognitive processes tapped by such tasks (Wolf & Katzir-Cohen, 2001). Wolf (1991) has suggested that the relationship between rapid naming or naming speed represents an index of automaticity for the lower level processes related to reading. Specifically, Wolf, Bowers, and Biddle (2000) conceptualize rapid naming as ‘a complex ensemble of attentional, perceptual, conceptual, phonological, semantic, and motoric subprocesses that place(s) heavy emphasis on precise timing requirements within each component and across all components.’(pp. 201) Since the initial publication of their findings, which suggested both a contribution of RAN to the prediction of reading disability separate from phonological awareness and the creation of three basic subtypes for dyslexia based on the absence or presence of RAN deficits, significant controversy has existed as to the utility of the double-deficit hypothesis and as to the nature of the underlying cognitive structures tapped by the RAN tasks (Wolf & Katzir-Cohen, 2001). While multiple studies have validated the use of the double-deficit hypothesis for children with reading disabilities (e.g., McBride-Chang & Manis, 1996; Morris et al., 1998), other researchers have suggested that this line of research suffers from an incomplete understanding of rapid naming and its relation to the underlying constructs as little research has sought to explicate these relationships empirically (Swanson, Trainin, Necoechea & Hammill, 2003). What is clear from research on rapid automatized naming, however, is that this aspect of reading depends, in some way not yet fully explored in the literature, on fluent integration of multiple cognitive processes, such as visual symbol recognition and phonological representation activation, in order to complete the task of reading.

Reading Disability/Dyslexia

Both phonological awareness and RAN have been supported as significant factors in the course of reading development (Manis, Seidenberg & Doi, 1999; Sunseth & Bowers, 2002; Wolf & Bowers, 1999). Deficits in both phonological awareness and RAN also have been consistently linked in the literature to reading failure associated with developmental dyslexia (hereafter dyslexia). Commonly, dyslexia has been defined as one aspect of a learning disability (LD). The definition of what constitutes a learning disability (LD), that is whether the disability is comprised of one or many factors, has been a major focus of research since the early 1960s (Shaw, Cullen, McGuire, & Brinckerfhoff, 1995; Vellutino et al., 2004). Some researchers have used reading as the litmus test for LD believing that students diagnosed with LD must show a significant deficit in at least one area of cognitive functioning related to reading performance (Silver, Pennett, Black, Fair, & Balise, 1999). Others have operationalized LD in more general terms viewing it as a disorder in one or more domains including: basic reading skills, listening, speaking, reading comprehension, written language, mathematics calculation, and mathematics reasoning (Lyon, 1994). This more general definition allows LD to encompass additional areas of dysfunction and suggests multi-directional influence among these areas. While a multi-directional view of learning disabilities may serve to associate multiple areas of dysfunction within a given child, specific hypotheses as to the underlying causes of dysfunction remain fractionated within the overall literature (Vellutino et al., 2004). Though multiple areas of dysfunction have been studied within the area of learning disability research, reading disabilities and their causes have received the most attention in the literature as compared to learning disabilities associated with mathematics or spelling (Geary, 1993). In many cases causal explanations for dyslexia, and subsequent diagnoses, have been supplanted by explanations dependent on observations of a child’s reading ability. For example, the utility of employing Bowers and Wolf (1993) double-deficit hypothesis depends on direct observation of the child’s apparent reading skill. The assumption is that both phonological awareness and RAN utilize lower-level cognitive structures and that dysfunction in these two higher constructs provides the signal that trouble exists within lower-level cognitive structures (Wolf & Bowers, 1999). An alternative to this line of investigation, however, is to build an integrative model of learning disabilities in which dyslexia represents one aspect of observable impaired behavior. This conceptualization allows for explanations for dyslexia and general learning disabilities that can be examined within these lower-level processes. A significant body of research suggesting a unifying connection within cognition has been suggested by Tallal and colleagues (1980; 2003) through their research on auditory processing.

Auditory Processing Disorder

In order to explain the theories of Tallal and colleagues regarding linkages between auditory processing and reading development, it is important to review the role of speech for language development. It has been suggested that all children are born with the ability to learn the orally presented language of their culture (Pinker, 1994). This process, however, requires several large feats of cognitive and linguistic processing by the child. Orally presented language does not make use of consistent stops within the speech stream that signal the end of one phoneme (i.e., smallest unit of sound in a word) and the beginning of another. For example, differentiating two basic syllables (/ba/ & /da/) requires that the child recognize brief, rapidly successive frequency changes within the acoustic wave form of speech. These changes are known as formant transitions. Recognition of these two syllables depends on the child's ability to process these initial consonant sounds within an average 40 millisecond formant transition, which are then followed by longer vowel sounds. Tallal and colleagues have demonstrated in their research that children with language learning impairments evidence deficits in their ability to process these brief, rapidly successive stimuli (Tallal, Stark, & Mellitis, 1985; Tallal, 2003). Tallal (1980) compared good and poor readers on a task requiring the processing of briefly presented complex nonverbal auditory stimuli. Each set of stimuli was 75ms in duration but varied in the time between presentations (i.e., interstimulus intervals, (ISI) between 8 and 305 ms). At the shorter ISIs, poor readers evidenced more difficulty discriminating between the complex tones than good readers. At longer ISIs, however, no differences between the two reading groups were observed. Further, of those poor readers that demonstrated deficits on the discrimination tasks, about half also evidenced deficits within a nonword reading task. A correlation of .81 was found for half of the participants between temporal order judgement and reading nonsense words (Tallal, 1980). Tallal suggested that the ability to process these rapidly changing acoustic events may be functionally related to the development of later phonological awareness.

This link between the ability to discriminate rapidly presented acoustic stimuli and phonological awareness grows out of theories regarding the neural firing patterns within the auditory cortex. Hebb (1949) hypothesized that simultaneously activated neurons are stored as a unit, or a specific pattern of neuronal firing that activates particular concepts. These units of commonly excited neuronal firing patterns are strengthened by repeated exposure or activation. The stronger the association between these neurons as impacted by exposure and activation, the greater likelihood that the units will be distinctly remembered and utilized to organize perceptually presented information. For Tallal and colleagues, the deficit in children's ability to rapidly discriminate these acoustic signals leads to weak associations between these stimuli and subsequently weaker neuronal firing patterns or units (Tallal & Piercy, 1975). In short, a child with an auditory processing deficit does not process the acoustic stimuli quickly enough to form and then strengthen these patterns and thereby forms weak associations on which to build phonological representations. Impaired phonological awareness has been consistently found as a primary deficit within dyslexia (Adams, 1990; Stanovich & Siegel, 1994).

Evidence also has suggested that this deficit in auditory processing may not be specific to audition or to later development of dyslexia. Waber et al. (2001) investigated the link between auditory processing deficits and reading development with a sample of 100 children with learning impairments and 243 children without learning impairments between the ages of 7 and

11. The children's learning impairment was not specific to dyslexia, but was characterized by global deficits in learning in spite of evidence for normal intelligence (i.e., a full scale WISC score above 80). Measures of academic achievement, including reading, were examined which allowed for statistical analyses comparing good and poor readers. The experimental task in this study required that the children discriminate between two steady-state, three formant complex tones which are perceived as non-speech stimuli. Both the length at which the tone was presented (e.g., 40, 75, & 250 ms) was varied as well as the ISIs separating the stimuli (e.g., 10, 50, 100, & 400ms). The 400ms ISI was utilized for training as previous research by Tallal and Piercy (1975) had suggested that discrimination at this ISI represented the easiest level for both good and poor readers. The remaining stimulus durations and ISIs were combined to form nine blocks of ten trials each for the testing procedure. Testing was carried out within the context of a 'Space Adventure' game in which the tones were presented as a means to differentiate two groups of miners required to supply a distinct type of candy to a dying planet. Results suggested that children with learning impairments did not show significant impairments in relation to either stimulus duration or ISI in comparison to children without learning impairments. Stated another way, both groups of children made significant errors at both short and longer stimulus durations and ISIs. The authors suggest that these results support the theory that auditory processing is but one factor among others that may contribute to deficits related to dyslexia.

Finally, Montgomery, Morris, Sevcik and Clarkson (2005) compared 52 children with and without dyslexia across seven auditory masking thresholds. In this study, a tone was presented to the right ear for either 20 ms or 200 ms and followed at different durations (-20ms, backward masking; 200ms simultaneous with tone; 300ms forward masking) by noise that was either bandpass noise (600-1400 Hz) or notched noise (1200-1600 Hz). Their results demonstrated that children with reading disabilities evidenced more difficulty separating a brief tone from a rapidly following noise of a similar frequency and more difficulty separating a brief tone from a rapidly following noise of a different frequency. As these tones do not represent linguistic information, the authors suggest that deficits related to reading disabilities may affect more processing areas than those specifically related to language processing in which language processing may be just one part of an overall deficit in relation to temporal processing (Montgomery et al., 2005).

Visual Processing Disorder

Another of the factors that may be implicated as underlying the development of dyslexia also builds upon notions of timing deficits in lower-level cognitive processes. Of these lower-level processes, researchers have sought deficiencies in the visual arena. Prior to the formation of theories regarding the phonological basis for dyslexia, the historical basis for dyslexia research employed theories that posited a deficiency within the visual system. Early researchers referred to dyslexia as a type of ‘word-blindness.’ In other words, the child exhibited normal parameters of sight, but was unable to process visually presented symbolic information. Samuel Orton suggested the term strephosymbolia to explain dysfunctions of cerebral dominance that led to unstable visual representations of letters and their order (Stein & Walsh, 1997). These distinctions were built upon the observation among children with dyslexia in which the transposition of letters (‘god’ for ‘dog’) is a common occurrence.

A recent review of eye movement research by Rayner (1998) outlines the way in which the eyes function during reading and highlights differences found between children with and without dyslexia. During the process of reading, the eyes are continuously in motion, an action referred to as saccades. A saccade is a rapid movement of the eyes with velocities upwards of

500 degrees per second. Between each saccade is a fixation, or when the eyes remain relatively still (200-300ms). The primary purpose of the saccade in reading is to bring a new region of text into foveal view for detailed analysis. For reading in English, the mean size of a saccade (or how many letters examined and brought into foveal vision) is about 7-9 letter spaces while fixations generally last between 200-250 ms. While most of the saccades occur in the direction in which the text is read (e.g., for English, left to right) about 10-15% of the time, the saccade occurs in the opposite direction, called a regression. These regressions may occur across words or within words but generally signal a need to reexamine some portion of the text that has already passed through foveal view (Rayner, 1998). The number and length of the regression has been linked to both the difficulty of the presented words and to the conceptual difficulty of the text (Slatterly, Pollatsek, & Rayner, 2006). In general, children evidence a developmental progression in relation to eye movements during reading such that saccades get longer while fixations get shorter and fewer regressions are needed as they age and gain more experience with reading. These changes lead to better reading efficiency and speed. Children with dyslexia, however, do not show the same developmental pattern in these areas (Lefton, Nagle, & Johnson, 1979). Moreover, children with dyslexia demonstrate more regressions when engaged in visual scanning of stimuli other than letters, such as following a dot across a screen (Pavlidis, 1981), suggesting a global deficiency in visual processing (i.e., in areas other than reading; Rayner, 1998).

The hypothesized source for this dysfunction of visual processing may lie within the magnocellular layers of lateral geniculate nucleus (LGN). Generally, the visual system processes information received through the retinal ganglion cells and primary visual cortex through the LGN. The LGN is comprised of six layers of two different types of cells involved in two different types of visual analysis: four dorsal parvocellular layers and 2 ventral magnocellular layers. Parvocellular layers receive spatially segregated color related input from small P cells in the retinal ganglia; these cells provide visual information related to color and space. Generally, these cells exhibit slower conduction through the system as their purpose has been interpreted by some to reflect an appreciation for the ‘whole’ of the visual field. Conversely, magnocellular layers of the LGN are generally faster in their conduction and concerned with information regarding the temporal sensitivity within the visual field; these cells process information faster as they are concerned with information regarding change and movement (Lovegrove, 1993). Lovegrove, Heddle, and Slaghius (1980) examined differences on visual store durations of using a common spatial frequency task utilizing sine-wave gratings at low and high spatial frequency in a sample of adolescents with developmental dyslexia. Their results indicated that individuals with dyslexia exhibit a pattern of reduced contrast sensitivity at low spatial frequencies and low luminance, two areas that employ magnocellular areas of the LGN. Conversely, no differences were found between children with dyslexia and children with typical reading abilities on contrast sensitivity, an area that employs parvocellular areas of the LGN. Further confirmation of these findings was demonstrated by Galaburda, Sherman, Rosen, Aboitiz, & Geschwind (1985) in a post-mortem study of the brains of four individuals with dyslexia. Their analysis of the LGN in these brains confirmed an overall disordered pattern within the magnocellular layers and a 20% reduction in the magnocells relative to control brains.

The relation between magoncellular deficits in the LGN and reading ability has been hypothesized to lie in their connection with the posterior parietal cortex (PPC). This area of the brain is dominated by magnocelluar-like cells that are particularly sensitive to direction of movement and direction of gaze, and particularly insensitive to aspects of color and visual form (Stein & Walsh, 1997). Slight impairments in the magoncellular layers of LGN may be compounded within the organization of the PPC which is known to be important to the coordination of eye movement, visual attention, and peripheral vision. All three of these areas have been found to be important in the enactment of reading (Martin & Lovegrove, 1984). For example, instability within the magnocellular layers has been found to impact the control of binocular fixation. Binocular fixation is necessary for the creation of a stable view; information from both eyes must be associated to create a ‘picture’ of the letters and words within reading. Further, deficits in the PPC may lead to a deficit for inhibiting the sustained information received through the parvocellular layers of LGN during saccadic eye movement. In other words, the magnocellular layer deficits related to the temporal analysis of information as the eye moves must compete with the longer interval information gleaned by the parvocellular layer (Rayner, 1998). This may lead to the superimposition of visual information causing visual confusion as to the form of the letters and words presented in text. In much the same way that the auditory system may not be able to discriminate between rapidly successive auditory cues in speech which impair the creation and substantiation of phonological representations, visual system deficits in discrimination between letters and words may lead to inefficient creation and substantiation of orthographic patterns (Helevang & Hugdahl, 2003; Stein & Walsh, 1997).

Taken together, the auditory processing and visual processing disorders describe two sides of the reading deficiencies exhibited by children with dyslexia. The primary question in the comparison of these two theories, however, is whether the deficits exhibited by children with dyslexia in these areas is best explained by two domain-specific deficits or by a global deficit related to temporally presented stimuli. Few studies have examined the role that both visual and auditory deficits play in individuals with dyslexia (see Farmer & Klein, 1995, for a review). Meyler and Breznitz (2005) examined both visual and auditory deficits in college age readers with dyslexia in tasks requiring the temporal processing of both linguistic and nonlinguistic stimuli presented in both visual and auditory formats. Thirty-seven adult students, including 18 individuals with dyslexia (8 women) and 19 individuals without dyslexia (9 women) matched on IQ, age, SES, and handedness were assessed on a battery of cognitive measures. Measures included working memory, reading (phonology, comprehension, orthographic processing) and speed of processing (Symbol search and Digit-symbol tasks of the WAIS-III). The experimental task consisted of discrimination between both visual and auditory rapidly presented stimuli for both linguistic and non-linguistic information. The visual stimuli condition consisted of discrimination between red and blue rectangular flashes (nonlinguistic) and between two CVC nonsense Hebrew syllables utilizing two easily distinguishable syllable patterns (i.e., ‘lak’ & ‘hab’). The auditory stimuli condition consisted of discriminating between two 1000 Hz tones (nonlinguistic) and two series of spoken CVC Hebrew nonsense syllables. The cross modal condition investigated the participants’ ability to recognize the same temporal rhythm across both a visual and auditory condition. In this case, discrimination was based on 1000 Hz tones compared to flashes of blue light (nonlinguistic) and auditory CVC sequences followed by visual CVC syllables presented in blue. ISIs for each condition were either 450ms or 200ms. The interval between each pair of discriminated stimuli was 1000ms. Each series of stimuli was presented twice in which three successive stimuli pairs were presented. The variable of interest relied on the temporal rhythm differences within the three stimulus pairs. For example, discrimination between (** *) and (***), where each asterisk represents a stimulus pair and each space an interval. Reaction time and accuracy were the primary means of evaluation.

A series of MANCOVAs were run for the unimodal and cross modal tasks. Results indicated that individuals with dyslexia were slower and less accurate in discriminating whether two temporal patterns comprised the same rhythmic structure. Differences were most apparent for discrimination between tone sequences and visual syllable sequences. While a general trend was found for poorer performance on linguistic versus. nonlinguistic stimuli for both dyslexic and nondyslexic groups, indicating an effect of processing load, pronounced deficits in both conditions for individuals with dyslexia suggest that neither auditory processing nor visual processing disorders alone are sufficient lower-level cognitive deficiencies to account for a disability in reading. Instead, Meyler and Breznitz (2005) suggest a global deficit for individuals with dyslexia for the processing of temporal information.

As this conceptualization of deficit for dyslexia comprises multiple areas of temporal processing deficiencies, other researchers have suggested that similar deficits may be found in areas not generally associated with the act of reading such as motor fluency and cerebellar functioning (Nicholson & Fawcett, 1999; Wolff, 1999). These theories mark a change in the investigation of mechanism deficits in lower-level processes associated with the integration of temporally presented stimuli from an examination of reading disabilities based on observable skill in reading related processes such as phonological awareness and rapid automatized naming.

Motor Fluency

If the deficit in reading disabilities is related to a global deficit in timing within the brain, it is possible that other aspects of the child’s development also may show timing related impairments. Following this line of research, Wolff and colleagues (Wolff, Cohen, & Drake, 1984; Wolff, 2002) have, in a series of studies, investigated the impact of timing deficits through the use of motorically based measures of functioning. The utility of using motor based measures to investigate cognitive processes has been a major tool for understanding multiple disorders, such as Parkinson’s disease and Schizophrenia, in both adults and children (Llinas, 1993). One advantage of using motor based measures is the accessibility by which complex motor patterns can be decomposed into component processes without overly altering the primary behavior (Wolff, 1999). Waber, Wolff, Forbes, and Weiler (2000) investigated this hypothesis with a large number of school-age children referred for learning impairment contrasted with children without learning impairment. Children were asked to follow a specific finger tapping pattern in time with different metronome based rates. Tasks were completed within three conditions: unimanual, bimanual, and symmetrical (or alternating). Performance on these tasks was then compared to measures of cognitive ability and scholastic achievement. Results indicated that children referred for learning impairments demonstrated deficits in following the rate set forth by the metronome across all three conditions. Further, these deficits accounted for significant variance in scholastic achievement measures (i.e., reading performance, mathematics, and spelling) after controlling for both cognitive ability (i.e., IQ) and gender. Significant to these findings, a deficit in motor timing control was found across all areas of scholastic achievement, not just within the arena of reading. This suggests the global interaction of motor timing to multiple areas of achievement and supports the utility of investigating motor based deficits as a means to understanding the etiology of reading disabilities. These researchers have found that individuals with dyslexia exhibit deficits on tasks that require rapid processing especially when information must be integrated across both hemispheres of the brain.

Further, Wolff (2002) investigated the ability of twelve children (5 girls) with dyslexia relative to a sample of age and gender matched children with average reading skills across three areas of motor control: anticipation of isochronic motor sequences, timing and serial ordering of rhythmic motor patterns, and the timing and serial ordering of motor speech or rate of speech production. Each of these three conditions were used to explicate the underlying hypothesis, supported by earlier research, that children with dyslexia exhibit an overall deficit in temporal processing that can be overtly measured by different aspects of motor control.

In the first condition, Wolff (2002) examined differences between the two groups in their ability to synchronize their responses on a finger tapping paradigm to an external pacing signal. Previous research had suggested that children and adults without a history of developmental problems typically anticipate the next beat of the external pacing signal (e.g., a metronome; Fraisse, 1982). This anticipation allows the individual to prepare for enactment of the required sequence and provides the basis for coordinated movement. In this condition, participants were asked to reproduce a particular rhythm represented by a metronome in two ways: with the index finger of the preferred hand, and then with both index fingers in unison. Performance was measured at ISIs of 670ms and 500ms. In the second condition, participants were informed that the metronome rhythm would change during the test. The metronome rhythm changed every 10 seconds increasing in hertz from 1.5 to 2.0 to 2.5 and finally back to 2.0. The participants were instructed to follow the change in the rhythm and respond in time with whichever frequency was presented. Finally, in the third condition the participants were instructed to reproduce a particular asynchronous rhythm that followed: their preferred rate (i.e., the rate at which the participant found reproduction most easy), 1/5th of their preferred rate (i.e., where the first tap coincided with the first beat of the metronome), or at 25% above their preferred rate.

Contrasting the performance of children with dyslexia to children without dyslexia demonstrated that children with dyslexia took longer to anticipate the next beat in the first condition, and took longer to switch rhythms in time with the metronome in the second. In the third condition, children with dyslexia exhibited more difficulty in terms of errors and arrhythmic pattern reproduction relative to children without dyslexia when attempting to reproduce a particular pattern of finger tap beats. Children with dyslexia demonstrated greater skill at production of a particular rhythmic rate when not paced by a metronome, but produced incomprehensible rhythms when asked to follow the metronome and with the rate set either below or above their preferred rate. In a second experiment, the same group of children with dyslexia and children without dyslexia were tested on motor speech repetition. Participants were asked to repeat 2-, 3-, and 4-unit strings of the CV syllable /pa/ as regularly as possible while stressing one designated syllable in each string. No differences between children with dyslexia and children without dyslexia were found on the 2-unit strings. Children with dyslexia, however, exhibited greater difficulty maintaining the pattern of stressed and unstressed syllables as well as demonstrating greater variability in the time between each syllable repetition for the 3- and 4-unit conditions relative to the children without dyslexia. The results indicated that the production of simple rhythms in either motor or motor articulation is relatively unimpaired in children with dyslexia relative to children without dyslexia, but that complex pattern production in response to environmental conditions (i.e., rate changes, metronome pacing, and stressed/unstressed discriminations) may be more taxing for children with dyslexia.

The sample of children, however, is small. Previous research by Wolff, Michel, and Ovrut (1990b) had investigated motor timing deficits in a larger sample of children with dyslexia (n=50) and demonstrated that only slightly less than half (46%) exhibited deficits in motor timing. Importantly, however, those that did exhibit motor timing deficits also performed worse on measures of reading ability relative to those children with dyslexia without motor timing deficits and a sample of gender and age matched children without dyslexia. In addition, in their investigation of possible subtypes within dyslexia, Morris et al. (1998) found that motor timing deficits did not characterize all subtypes of dyslexia, but instead motor deficits were found to be associated with a particular subtype that also exhibited deficits in both phonological awareness and rapid automatized naming. This subtype was in contrast to those individuals in which only phonological or only rapid automatized naming deficits were evident. These subtype differences are similar to those suggested by Wolf and Bowers (1999) within their theory of a double-deficit for dyslexia.

Oral Diadochokinesis

Given the large role of linguistic processing within reading, multiple researchers have sought motor fluency differences between children with dyslexia and children without dyslexia by examining differences in oral diadochokinetic rate. Diadochokinesis is defined as the performance of rapid, alternating, and repetitive bodily movements such as opening and closing the jaws or lips (Wolk, Edwards, & Conture, 1993). For the purposes of this document, diadochokinetic rate will be discussed exclusively in relation to articulation though it could be used descriptively for all patterned body movements. Oral diadochokinetic rate typically is assessed through a maximum repetition rate (MMR) paradigm, or the amount of time necessary to orally repeat a specific CV, CCV, or CCCV syllable structure. Tiffany (1980) found that diadochokinetic rate did not correlate with overall speech rate due to the prosodic and contextual inflections necessary for representing the common spoken form of English in a small sample of adult readers without evidence of dyslexia. Similarily, Portnoy and Aronson (1982) examined diadochokinetic rate in a larger sample of older adults with either spastic or ataxic. Their results indicated that individuals with motor control problems demonstrated significantly slower MMR for the monosyllables of /pa/, /ta/, & /ka/ relative to age matched participants with out deficits in motor control. Further, participants with motor control problems demonstrated a great deal more variability for within group MMR, specifically those participants with spastic dysarthria.

Much less research has investigated diadochokinetic rate in children or its possible relationship to reading and dyslexia. Hypothetically, diadochokinetic rate assesses the amount of time required to access and process the motor gesture needed to form the sound of a particular syllable repeatedly over time, a model for the temporal programming of speech. As these motor gestures are intimately linked to phonological representations, some researchers have hypothesized that overall deficits in phonological processing should be evident through examination of the MMR in a diadochokinetic rate task. Wolk et al. (1993) investigated MMR differences between children who stuttered and exhibit disordered phonology and children who stuttered but did not exhibit disordered phonology. Disordered phonology was determined through an examination of the child’s speech and the presence of two or more ‘unusual’ or ‘atypical’ pronunciations, such as incorrect syllable stress or vowel pronunciation. These two groups were compared to children who did not stutter or demonstrate disordered phonology. The child was instructed to repeat monosyllabic and/or multisyllabic patterns. While Wolk et al. (1993) did not find differences across the three groups of children in diadochokinetic rate, children with disordered oral phonology did make more syllable mistakes than children without disordered phonology. Wolff et al. (1984) studied a small sample of boys with dyslexia on a similar measure of oral diadochokinetic rate and compared their performance with a sample of boys with general learning impairments. Further, this sample of boys was divided into two age groups, late elementary school (10-12) and adolescents (15-18). These researchers demonstrated that the boys with and without dyslexia had similar MMRs for monosyllable presentations of /pa/, /ta/, and /ka/. When compared, however, on longer syllable patterns (/pataka/), boys with dyslexia in both age groups demonstrated longer MMRs and made significantly more errors in repetition.

Wolff, Kotwica, and Obregon (1998) examined children's general articulation rate, not specific to diadochokinetic rate, during a rapid automatized naming task. Utilizing a computer program to digitize the speech pattern of children with and without dyslexia on a rapid naming task, Wolff and colleagues segregated each articulated sound as an 'island' within the speech stream. In other words, the program allowed the isolation of discernable morphemes and phonemes within the speech stream. These researchers demonstrated that the difference between the two groups on the rapid naming task was not the result of differences in the time required neither to scan the visually presented stimuli nor to form the articulation patterns, but instead differences were found in the ISIs between each 'island.' These findings suggest that the deficit is not in the execution of motor based responses, such as visual scanning or articulation, but instead on the enactment of these motor patterns within temporally based rapidly successive stimuli presentations.

Researchers also have examined motoric fluency within groups of children exhibiting both phonological and rapid naming deficits. Waber, Wolff, Forbes and Weiler (2004) investigated whether the double-deficit theory of dyslexia interacted with other neuropsychological domains, such as motor timing, in addition to reading. In their sample of 188 of children who ranged in age from 7-11 years referred for learning impairments, children were classified according to the outlines of the double deficit hypothesis: no deficit (n=57), naming speed deficit (n=100) and double-deficit (n=28). The fourth category of a phonological deficit alone was comprised of only three individuals whose scores were exceedingly close to the cutoff of 1 SD below the average on tasks of rapid automatized naming (i.e., .87 & .92) and were considered an artifact of data error. Children characterized by the double-deficit demonstrated lower scores on all motor measures, but when these motor measures were divided into those requiring motor sequence learning and motor speed control, significant differences were found only between those children with no deficit and those exhibiting either only a naming speed deficit or both a phonological and naming speed deficit. In other words, those children characterized by the double-deficit were not significantly different in their ability to integrate a stimulus cue with a decision and a motor response from children with a naming speed deficit alone.

Taken together these studies suggest that some level of motor timing impairment can be found in individuals exhibiting deficiencies within two areas highly associated with developmental dyslexia: naming speed and phonological awareness. Deficits of motor timing, however, were not found across these studies for all children exhibiting learning impairments. Instead, motor timing deficits in relation to temporally presented stimuli may explain observed problems in children with dyslexia for only half the population; those exhibiting the most difficulty in relation to reading also exhibited the greatest difficulties with measure of motor fluency. Moreover, the majority of these studies have employed samples characterized by general learning impairments not specific to the reading difficulties within dyslexia.

Cerebellar Deficit Theory

Other researchers have sought to connect motor processing problems with a specific area of the brain. The role of the cerebellum in the planning, execution, and automatization of motor skills has been well substantiated by multiple researchers (Fawcett, Nicolson, & Maclagan, 2001; Merzenich et al., 1996). Further, research also has suggested that the cerebellum plays a role in specific reading activities. Fulbright et al. (1999) investigated the role of the cerebellum in 42 (23 women) adults without evidence of neurological impairment across three basic reading tasks: orthographic processing (i.e., discriminate whether words were written the same), phonological assembly (i.e., whether words and non-words rhymed) and semantic processing (i.e., whether pairs of words belonged to the same category). Reading tasks consisted of four yes/no trials within each condition (i.e., did the words rhyme or not or were the words written the same or not). Participants performed baseline perceptual tasks consisting of judgments of yes or no to the sameness of different line angles (e.g., /, / or /, \). Participants were scanned using a 1.5-T functional magnetic resonance unit. A series of t-tests were conducted to compare baseline activity in the cerebellum with activity recorded during each reading trial. The results indicated activation in the middle and posterior aspects of the posterior superior fissure and adjacent simple lobule of the cerebellum during phonological assembly tasks. Further, a different pattern of activation within the cerebellum was found for semantic processing within the inferior vermis and right-side of the deep nuclear region (Fulbright et al., 1999). These findings support the role of activation within the cerebellum in relation to reading

Other studies have investigated the relationships between different aspects of motor skill and reading skill. Fawcett and Nicolson (1999) contrasted performance on three experimental tasks related to cerebellar functioning in both children with dyslexia (n=59) and age-matched children without dyslexia (n=67). The three tasks consisted of postural stability (i.e., the degree of sway when pushed from a standing position with a 2 kg force), arm shake (i.e., shaking the participant’s arm to assess the degree of movement), and toe tapping (i.e., the time taken to make 10 toe taps). These tasks were compared to reading tasks of phonemic segmentation, nonsense word repetition and picture naming speed. Children with dyslexia were found to exhibit poorer scores on all measures of cerebellar functioning relative to children without dyslexia. Further, poorer performance in postural stability and large arm shake movements, indicating poor muscle tone, were found to be significantly related to both phonemic segmentation and nonsense word repetition. These results, however, are not without limitations. Children with dyslexia selected for this study were drawn from specific schools or school based units specializing in the remediation of phonological skills related to reading. As such most of the children with dyslexia were enrolled in classes designed to address reading skill development (Fawcett & Nicolson, 1999). To date, however, the possible relationship between reading related interventions and changes in motor fluency and control has not been investigated. This possible confound, however, was not neither postulated as a factor, controlled for in analysis, nor explicated as a possible limitation.

Moreover, Nicolson and Fawcett (1994) suggested that cerebellar deficits in relation to reading and motor based measures of functioning represent a fundamental disorder associated with the overall impaired development of automization. Nicolson and Fawcett (1999) have conceptualized this overall deficit in automization as a Developmental Automation Deficit (DAD) and suggest that children with dyslexia are unable to demonstrate automatized behavior within any task. These findings were followed by another study by Fawcett et al. (2001) in which the same children with dyslexia were reclassified as either IQ-discrepant or IQ-nondiscrepant poor readers in addition to two age matched control groups. Participants were evaluated on multiple tasks designed to assess different aspects of cerebellar functioning (e.g., both static and dynamic) as well as tasks of phonological processing, verbal memory, and processing speed. Static cerebellar tasks were those hypothesized to tap aspects of dystonia (i.e., problems with muscle tone) while dynamic cerebellar tasks were those hypothesized to tap aspects of ataxia (i.e., disturbance in posture, gait, or extremity movement). The design of the study was such that each area of these tasks was selected to build upon one or more of the major hypotheses set forth for explaining the cause of dyslexia in children: phonological, visual speed, auditory processing, motor fluency, and cerebellar. Results indicated that children with dyslexia as defined by an IQ-discrepancy and children with dyslexia without an IQ-discrepancy had lower scores on all 17 tasks assessed than children evidencing typical reading development. Further, relationships between static cerebellar functioning were found for children with dyslexia that exhibited an IQ-discrepancy but not for children with dyslexia without the IQ-discrepancy. In addition, based on the predictions of performance on these tasks across each of the investigated hypotheses, only the cerebellar hypothesis for dyslexia correctly predicted the observed pattern of performance. Other theories such as the phonological deficit only, naming-speed only and double-deficit theory of Wolf and Bowers (1999) were supported but did not significantly predict performance on all measures of motoric functioning. Fawcett et al. (2001), therefore, suggest that these findings support their hypothesis regarding overall deficits in children with dyslexia for automization. The trouble with this conceptualization, however, is that while deficits in relation to cerebellar functioning may differentiate children with dyslexia from children without dyslexia, any evidence of automatization within a population of children with dyslexia, regardless of the task, invalidates the basic assumption of this theory as it posits a global deficit in automatization (Savage, 2004).

The previous review of the prominent theories for the underlying cause of dyslexia in children has highlighted the multiple ways in which researchers have investigated the myriad of observed deficits in relation to observed reading skill, that is, perceptual processing, temporal processing and cerebellar-supported motor functioning. For the most part, these investigations have focused on relatively small sample sizes. Moreover, while most of the studies above have investigated the role of phonological processing and naming speed in relation to dyslexia, few have examined the role of reading fluency, with the notable exceptions of Wolf and Bowers

(1999). Specifically, theories suggesting temporal processing deficiencies evidenced through motor fluency and those regarding the evidence of cerebellar dysfunction within dyslexia have yet to investigate their applicability to reading fluency.

Reading Fluency

The emphasis on investigating reading fluency in relation to the remediation of dyslexia in children has increased in recent years. The impetus for this focus has arisen as the result of successful remediation of phonologically based problems observed within children with dyslexia (Torgesen, 2005). Improved processing of phonological material in relation to reading, however, may only represent one part of remediating the observed reading skill in children with dyslexia. Many children who have successfully completed remediation programs focused on phonological decoding do show improvements in single-word decoding, one of the best predictors of later reading success (Stanovich & Siegel, 1994), yet continue to exhibit difficulty in applying these skills within connected text. In other words, these children now possess the requisite skills for word decoding yet seem unable to enact the phonological decoding process in an efficient way leading to observable deficits in the overall fluency or speed with which they are able to interact with both connected text and single word reading. As such new efforts within the field of dyslexia research have been directed toward understanding this concept of reading fluency, its constituent parts, and effective means by which to affect its remediation. This effort in dyslexia research and overall reading research was affirmed by a National Reading Panel commissioned by the National Institute for Health and Child Development in 2001. Their findings cited the need for increased understanding of the relationship of fluency to reading and for research into the best methods for affecting fluency in reading remediation (National Reading Panel, 2001). Research on fluency has generally fallen into two camps that differ fundamentally on the role of fluency in the reading process: 1) ‘fluency’ represents a dependent variable and acts as an index for the quality of reading (Fuchs, Fuchs, Hosp, & Jenkins, 2001); and 2) ‘fluency’ represents an independent variable in which variation affects the quality of reading (Breznitz, 2001; Wolf & Katzir-Cohen, 2001). Research regarding measures of fluency as dependent outcomes of the reading process supports the view of fluency as ‘the ability to read connected text rapidly, smoothly, effortlessly, and automatically with little conscious attention to the mechanics of reading’ (Meyer & Felton, 1999, 248). More generally, the National Institute of Child Health and Human Development has defined fluency as ‘the immediate result of word recognition proficiency.’(National Reading Panel, 2001). This view of fluency proposes that fluency can be achieved only after basic word reading skills are mastered. In addition, this view does not encompass a developmental perspective on the growth of fluency as a cognitive factor as it is conceptualized as an end result of reading development and not a contributing factor. This limits the ability of this hypothesis to address changes in fluency as it is viewed as an end result and not a growing, integrative cognitive process. A developmental perspective on fluency posits that fluency grows across multiple areas of cognition during the reading acquisition and automatization process. Wolf and Katzir-Cohen (2001) have set forth a definition of reading fluency that incorporates the following view of development:

> ‘Reading fluency is the product of the initial development of accuracy and the subsequent development of automaticity in underlying sublexical processes, lexical processes, and their integration in single word reading and connected text. These include perceptual, phonological, orthographic, and morphological processes at the letter, letter pattern, and word levels, as well as semantic and syntactic processes at the word level and connected text level. After it is fully developed, reading fluency refers to a level of reading accuracy and rate where decoding is relatively effortless; where oral reading is smooth and accurate with correct prosody; and where attention can be allocated to comprehension.’(p. 219)

Drawing upon the theoretical causes of dyslexia described previously, a hypothetical model of fluency development and its relationship to reading development can be postulated. Fluency develops through accurate processing (i.e., both visual and verbal information) and, assuming accurate processing, the formation of discrete long-term memory representations that can be accessed and utilized automatically, or with little cognitive effort. Further, this process occurs across these interrelated levels of lexical processing. As the goal of automaticity is desired at every level, this multi-level lexical system operates as a parallel-distributed process such that development is occurring at all three levels and is mutually dependent on the growth across these levels. In other words, as lower level lexical patterns are established (i.e., perceptual and phonological distinctions), larger level lexical patterns begin to be formed and established as chunks in long term memory (i.e., common orthographic pairings and morphological groups). The larger numbers of known and established chunks pave the way for increasing a child's exposure to different word combinations building first upon the initial chunks then by providing a basis for linguistic decoding through analogy, rhyming, and overall similarity. These more complex words then feed new phonological groupings and orthographic chunks into the lower level lexical processes which perpetuates the cycle of automaticity. Growth in fluency is, therefore, the adequate integration of all types of lexical information at both each individual level and across levels. Given the importance of integration within this conceptualization of fluency and the opposing hypotheses for the underlying cause of dyslexia outlined previously, the main question becomes which hypothesis offers the best explanation for the foundation of fluency deficits in children with dyslexia. In exploration of these foundations for dyslexia, Wolf and Katzir-Cohen (2001) have suggested, in their definition of fluency, that the answer may lie in a better understanding of how the lower-level cognitive processes, such as temporal processing and, by extension, the relationship to overall motor functioning, affects the dominant focus on phonological processing and rapid automatized naming in the development of effective reading skill.

Specific Hypotheses

The primary purpose of this dissertation is to investigate the relationship between measures of motor fluency, phonological awareness, rapid automatized naming, and reading fluency for young children with reading disabilities. It is expected that motor control will contribute to the prediction of fluency based single word reading both directly and indirectly through measures of phonological awareness and rapid automatized naming. As motor control is hypothesized to represent observable behavioral measures of temporal processing (Wolff, 1999), it is important to consider the latent factor structure within the battery of utilized motor measures. Previous research focusing on motor control in reading disabilities has not investigated whether these measures represent a consistent factor structure in young children with RD (Vitiello, Ricciuti, Stoff, & Behar, 1989). The first hypothesis of this proposed study concerns the nature of this relationship: What is the relationship between measures of motor control in young children with reading disabilities? Based on Wolff and colleagues' research (1992; 1999), and the overall design of the measures, it is expected that three distinct latent constructs will be identified: repetitive movements, patterned movements, and oral motor movements.

A second purpose of this proposed study is to examine the relationships that exist between these motor measures and measures of phonological awareness, rapid automatized naming and reading fluency. No study has attempted to model the influence of motor measures on reading disability either directly on reading fluency or through other component factors of reading. The second hypothesis of this proposed study concerns the relationship between the factor structure of the motor measures explicated in the first hypothesis and measures of reading and reading fluency: Does this motor factor structure relate to reading fluency independently or through other factors related to reading development? It is hypothesized that the relationships will be strongest between motor measures, rapid automatized naming, and reading fluency. It is expected that the relationship between motor measures and phonological awareness will operate through measures of rapid automatized naming. In addition, it is expected that motor measures will be directly related to measures of reading fluency above and beyond measures of phonological awareness and rapid automatized naming.

Methods

Participants

The proposed study utilizes archival data from a large multi-site longitudinal study examining reading intervention effects on young school aged children. Children were selected from public and private second and third grade classes in three large metropolitan cities: Atlanta, Toronto, and Boston. Children were initially recruited on the basis of teacher referral and his/her observation of their early reading ability. The participants were either African-American (or African Heritage) or Caucasian, had hearing and vision within normal limits, and English as their primary language. One hundred and fifty-two participants were African American or of African Heritage while 153 were Caucasian; 40.0% (n=122) were female students and 60.0% were male. Their mean chronological age in months at the time of referral was 89.64 (SD=6.43), and ranged from 77 to 108 months.

Children were excluded from the study if they had repeated a grade, had a history of psychological/neurological disorder and/or a (Kaufman Brief Intelligence test; K-BIT) composite score below 70 (Kaufman & Kaufman, 1990). Children were not excluded for the presence of disorders commonly associated with reading disability, such as Attention-Deficit Hyperactivity Disorder. Children meeting the criteria were included in a large, multi-site treatment intervention program focused on the improvement of reading skill.

Operational Definition of Dyslexia

A series of intellectual and reading skill assessments were obtained to determine the presence of a reading disability. Three subtests were used to determine the child's overall reading achievement level: the average of the standard scores of the Woodcock Reading Mastery Test-Revised (WRMT-R) Word Identification, Passage Comprehension, Word Attack (Woodcock, 1987); the standard score from the WRMT-R Total Reading cluster short-form (Word Identification and Passage Comprehension subtests); and/or the standard score of the WRMT-R Basic Skills Cluster (Word Identification and Word Attack; Woodcock, 1987). Participants were selected for the study if they met one of two criteria: Low Achievement (LA) and/or Ability Achievement Regression Corrected Discrepancy (AA-D). Children with a K-BIT composite score above 70 and whose reading skills were equal to or less than a standard score of 85 were identified under the LA criteria. Children whose actual reading performance was at least one standard error of the estimate below their Expected Achievement Standard Score (EASS) were included under the AA-D criteria. EASS was calculated based on an average correlation of .60 between reading skill and intellectual ability.

If a child met the study criteria, he/she was randomly assigned to one of four intervention conditions with the restriction that no cell (based on the original 2 (socioeconomic status; Lo/Hi)

X 2 (race; AA/Cauc) X 2 (IQ level; Lo/Avg) factorial design developed by the study's researchers) contained more than 5 students from any one of the three collection sites.

Procedure

Referred children were given a recruitment packet to take home that contained a description of the study and a consent form. Children who returned a signed consent form were screened for the study. Psychologists or doctoral trainees who were trained in test administration conducted testing. All measures were administered in the children's schools and during second or third grade in the years spanning 1996-2000.

Measures

Rapid Automatized Naming (RAN)/ Rapid Alternating Stimuli (RAS; Denckla & Rudel, 1974; Denckla & Rudel, 1976b). The RAN/RAS tasks measure naming speed and accuracy for objects, numbers, letters, and a combination of letters and numbers. Measure include the latency to name 50 items arranged in a 10x5 format reading from left to right and the number of errors made.

Word Reading Efficiency (Torgesen & Wagner, 1996). The WRE includes two lists (A & B) of 104 actual words that increase in difficulty. The mean number of words read on both forms in 45 seconds provides a measure of reading efficiency. This is a subtest of Comprehensive Test of Reading Related Phonological Processing (CTRRPP), the research version and precursor to the *Test of Word Reading Efficiency* (TOWRE; Torgesen, Wagner, & Rashotte, 1999).

Timed Word Reading Tests (Lovett, Barron, & Forbes, 1994)**.** Two timed, computer-administered word identification tests measured word identification ability and its level of automaticity. The first of the two tests was the computer Keyword test (120 words), which included regular words with high frequency spelling patterns. Keywords were adapted from the keyword list introduced by the *Benchmark School Word Identification/Vocabulary Development Program* (Gaskins, Downer, & Gaskins, 1986). The second computer list contained words assessing transfer of learning. The computer Test of Transfer included 120 words that were systematically related to words that were to be taught to some participants once involved in an intervention. Participants had no exposure to either set of word lists at the baseline timepoint utilized in this analysis.

Elision and Blending Words. (Torgesen & Wagner, 1996). The Elision subtest measures the ability to parse and synthesize phonemes, whereas the Blending subtest measures the ability to combine phonemes into words. These subtests are part of the CTRRPP (Torgesen & Wagner, 1996). The Blending and Elision subtests have been updated into the subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999).

Sound Symbol Test (Lovett et al., 1994). This experimental measure is designed to test the awareness of phonology through the graphic presentation of letters and letter combinations in isolation that the participant is required to name. The test is comprised of four subtests: 1) Letter-Sound Identification, which includes 37 items that target the sounds that the individual letters of the alphabet make; 2) Onset Identification, which includes 15 letter combinations that frequently appear at the beginning of words; 3) Rime Identification, which includes 25 letter combinations that frequently appear at the end of words; and 4) Sound Combinations, 30 letter combinations that frequently appear within words.

PANESS (Denckla, 1974): The Physical and Neurological Exam for Soft Signs. This test is designed to assess motor function. It was normed on 168 elementary school children with average IQs and school achievement (Vitiello et al., 1988). The PANESS includes several subtests within different categories of movement; only those assessing repetitive timed and patterned time movements were utilized. Repetitive timed movement subtests include: hand patting, finger tapping, and foot tapping. Patterned timed movements include: hand pronation-supination, finger apposition (tapping the thumb to each of four other fingers on each hand in a fixed sequence, and heel-toe tapping. Reaction time was assessed in each subtest. In repetitive timed and patterned timed movement subtests, the time to complete 20 movements was recorded using a stopwatch.

PA-TA-KA (Denckla, 1974). This task is designed to measure oral diadochokinetic rate. In the first part of the task, participants were asked to repeat several simple monosyllabic productions (i.e., /pa/, /ta/, & /ka/) after a practice trial to introduce the task. In the second part of the task, participants repeated a complex multisyllabic production utilizing the same three basic monosyllables (i.e., /pataka/). Diadochokinetic rate was determined by the number of seconds it took the participant to produce 10 repetitions of the target syllable sequence. Errors of production also were recorded.

Finger Tapping Task. (Bornstein, 1985; Klonoff & Low, 1974). This test is comprised of measuring the number of seconds required to produce a simple cadence demonstrated by the examiner with the index finger of both the dominant and nondominant hand. The number of repetitions completed in 10 seconds was recorded. Errors and indications of overflow also were recorded.

Results

Initial analyses involved a data screening process carried out to identify outliers, missing data, unusual data points, or atypical distributions that may require transformations before analyses can be conducted. Screening analyses were conducted using the Statistical Package for the Social Sciences 14.0 (SPSS).

Of the 305 study participants examined at the baseline timepoint, multiple participants were found to be missing several data points. Participants missing three or more data points across the variables of interest were excluded from the data base. Further, multiple participants were missing two or fewer data points across the variables of interest. In order to preserve the largest number of participants available, participants missing less than two data points were reserved within the final database and missing data points were estimated using regression based on the highest correlated variable. For example, participants missing two or fewer scores on subtests of the PANESS were estimated using the highest correlated subtest of the PANESS without any missing values. The Nonword Reading Efficiency subtest was not included in the analyses due to a large number of missing scores. As this variable represents one measure of the word reading fluency and a significant aspect of the hypotheses examined, it was important to exchange this variable for another measure of word reading fluency. The Keyword and Transfer subtests of the Timed Word Reading tasks were added to the analyses. These measures evidenced high correlations between each other and with the other measure of word reading fluency, the Word Reading Efficiency subtest. Both subtests were included in all subsequent analyses. The final sample for analysis was composed of 255 participants of which 40% were female, 49% were of African Heritage, and 45% were of Low SES status. Means, standard deviations, and ranges are included in Table 1. Measurements are displayed relative to their hypothesized relationship to analyzed constructs. In addition, normative scores are included for subtests of the PANESS (Barron, 2004), CTRRPP and WRE (Torgesen & Wagner, 1996), and PATAKA tasks (Fletcher, 1972). Percentages indicate the proportion of children within this sample that fall outside the normal range.

Table 1. Means, Standard Deviations (SD) and Range, and Normative score range for measured variables in analysis by hypothesized construct (N=255)

Hypothesized Construct	**Measured Variable**	**Mean**	**SD**	**Range**	**Norm Range**	**% of sample**
Repetitive Motor Movement	*Finger Tapping Task*	31.63	4.39	18.55-45.70	23.85-32.75	36%
	PANESS:					
	Finger Tapping	6.32	1.06	1.66-11.34	5.98-6.29	49%
	Hand Tapping	4.82	.916	3.06-8.28	4.52-5.12	30%
	Foot Tapping	7.89	2.25	4.55-18.47	5.51-6.34	73%
Patterned Motor Movement	App. Finger Tapping	11.97	3.52	5.90-31.24	10.10-11.95	46%
	Hand Pronate/Suppinate	7.40	1.90	4.13-17.51	7.27-8.17	26%
	Foot-Heel-Toe Tapping	10.10	3.37	4.29-31.04	8.02-9.18	55%
Oral Motor Movement	*PATAKA:*					
	PA	5.45	1.35	3.21-11.39	4.2-4.8	65%
	TA	5.51	1.36	3.05-12.02	4.4-4.9	64%
	KA	5.87	1.43	3.12-15.17	4.8-5.3	61%
	PATAKA	10.50	4.27	2.00-31.34	8.3-10.0	46%
Phonological Processing	*CTRRPP*					
	Blending	9.42	4.62	0-23	Experimental	
	Elision	8.46	3.78	0-25		
	SOUND/SYMBOL					
	Letter-Sound ID	21.86	8.10	0-37		
	Onset ID	4.98	4.30	0-15	Experimental	
	Rime ID	4.43	5.11	0-24		
	Sound Combinations	4.98	4.30	0-24		
Rapid Automatized Naming	*RAN/RAS:*					
	Letter	21.86	8.10	22-128		
	Number	48.35	17.83	25-162	Experimental	
	Alternating	68.46	33.90	33-308		
Word Reading Fluency	*Word Reading Efficiency*	24.47	18.32	0-86		
	Timed Word Reading				Experimental	
	Word ID-Keywords	13.94	10.37	0-39		
	Word ID-Transfer	4.07	6.13	0-28		

Latency for PANESS, PATAKA, and RAN/RAS measured in seconds. Word Reading fluency tasks measured in number of words read per time limit. Percentages represent the proportion of participants in this sample demonstrating scores outside the normal range for standardized measures: PANESS (Barron, 2004), CTRRPP and WRE (Torgesen & Wagner, 1996), and PATAKA tasks (Fletcher, 1972).

Normality and Outliers

All measures utilized in this analysis were examined for univariate outliers. Significant outliers were identified through z-score analysis. Those participants with a z-score greater than +/- 3.3 were adjusted to the next highest score within three standard deviations of the mean for that variable. This change was needed only for the Rapid Alternating stimulus variable and the Rapid Letter naming variable. Further, after adjusting for univariate outliers, all variables of interest were submitted to a Mahalanobis distance test of multivariate normality (Kline, 1998). This test evaluates the distance of particular cases from an overall centroid mean estimated from the distributions of all variables of interest. The resultant values are then distributed across a normal distribution that is comparable to an x^2 distribution. A stringent significance level of .001 was used to evaluate multivariate departures from normality. Three participants were found to be significantly different from the centroid mean at the .001 level and were subsequently omitted from the analysis. These participants were found to have significant outliers on multiple measures of motor functioning relative to both their age and the outcome measures of reading fluency.

Skew and kurtosis analyses for all measured variables revealed several departures from normality. This was not unexpected given the nature of the reading disability status for all participants. As the intent of this analysis is to examine the relationships between measures of motor fluency and reading development related variables in young children with reading disabilities and, therefore, demonstrating significant deficits in reading related processes, it is important to consider the full range of scores within this sample. All measures of skew were below .8 and kurtosis below .10. Kline (1998) has suggested that this level of departure from normality has a limited effect on the outcomes of model comparison in samples in which the parameter to observations does not exceed 10 to 1 and the sample is over 200. The resultant sample utilized for both hypotheses consists of 255 participants with a parameter ratio of 9 to 1.

Finally, an examination of the available normed scores for the subtests of the PANESS, PATAKA, and Finger Tapping Task revealed that this sample of children with reading disabilities exhibited moderate impairment on motor based assessments. The percentage of participants demonstrating scores outside the established norms ranged from 73% (PANESS Foot Tapping) and 65% (PA of PATAKA) to 26% (PANESS Hand Pronate/Suppinate Tapping) and 46% (pataka of PATAKA).

Correlations

Correlations were examined between the measures at the baseline time point. This analysis allowed for the examination of the relationships among predictor variables, relationships among outcome variables, and the relationship among predictor and outcome variables. Analyses were conducted on the measured variables of interest after adjusting for both outliers and normality. Initial correlations across the Left and Right hand subtests of each PANESS subtest utilized in this analysis revealed significant positive relationships above .7. In the interest of both parsimony, and that the ratio of parameters to observations would exceed that which is suggested for structural equation modeling (Kline, 1998), these subtests were combined to reflect an average for each motor subtest. These averages were used in all subsequent analyses. The pattern of relationships between these averaged subtests and fluency outcome variables of interest were not significantly changed by these amalgamations (Table 2). Correlations among these variables varied from nonsignificant to moderately significant (.62) with the exception of correlations between measures of word reading fluency (.91). The Finger Tapping Task was found to have a negative relationship to all other measures of motor functioning. This task differs from the other motor measures (i.e., subtests of the PANESS) in that this task measures the rate at which the individual participant can complete 10 repetitions of a motor cadence. The score then reflects the time required per repetition. This score is contrasted against the total time required to complete the movements within each subtest of the PANESS. All PANESS subtest scores were converted to the same metric of rate (i.e., time per repetition) and correlational analyses were conducted again. The pattern of association between the Finger Tapping Test and the other motor measures did not change. As the intent of this analysis is to explore the pattern of relationships across measures of motor fluency, the Finger Tapping Task was conserved through subsequent analyses, but was analyzed as to its validity within the model during model comparison analyses. Though wide ranging in their level of correlation, suggesting an unclear pattern of association between the observed measures, the amalgamation of these measures into latent factors allows for the explication of perfectly reliable unique variance shared across these measures.

Table 2. C*orrelations among measured variables (N=255)*

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
PAN: Finger	–																							
PAN: App Finger	**.21**	–																						
PAN: Hand	**.35**	.05	–																					
PAN: Hand P/S	**.35**	**.27**	**.70**	–																				
PAN: Foot	**.36**	**.23**	**.35**	**.35**	**–**																			
PAN: Foot-Heel-Toe	**.19**	**.33**	**.14**	**.34**	**.42**	**–**																		
Finger Tapping	**-.38**	**-.20**	**-.30**	**-.23**	**-.19**	**-.24**	**–**																	
PAN: Tongue Speed	**.14**	.07	**.14**	**.19**	**.17**	**.23**	**-.19**	–																
PATAKA: Ka	**.19**	**.15**	**.13**	**.16**	**.17**	**.13**	**-.19**	.04	–															
PATAKA: Pa	.09	**.13**	**.14**	**.14**	.08	**.17**	**-.21**	.03	**.59**	--														
PATAKA: Ta	**.13**	**.16**	.12	**.14**	**.17**	**.22**	-.25	-.02	**.68**	**.73**	--													
PATAKA: Pataka	**.13**	**.20**	**.16**	**.12**	**.19**	**.22**	**-.19**	.03	**.31**	**.36**	**.31**	--												
Blending	.02	-.08	-.10	-.01	-.08	**-.16**	.09	-.11	-.09	**-.14**	-.12	**-.20**	--											
Elision	-.06	**-.20**	-.12	**-.15**	**-.13**	**-.24**	.11	**-.14**	**-.19**	**-.14**	**-.16**	**-.18**	**.57**	--										
Letter-Sound ID	-.06	-.10	**-.15**	**-.16**	-.11	-.05	.10	-.04	-.09	-.09	-.03	**-.12**	**.61**	**.53**	--									
Onset ID	-.05	**-.21**	**-.20**	**-.16**	**-.15**	**-.14**	**.15**	-.03	**-.12**	-.10	**-.17**	**-.23**	**.56**	**.56**	.62	--								
Rime ID	-.10	**-.26**	-.12	**-.22**	**-.18**	**-.18**	**-.15**	**-.15**	**-.16**	-.12	**-.14**	**-.15**	**.57**	**.60**	**.62**	**.71**	--							
Sound Combo ID	-.20	**-.24**	-.10	**-.19**	**-.18**	**-.13**	.08	-.12	**-.17**	-.08	-.11	**-.13**	**.44**	**.49**	**.56**	**.63**	**.74**	--						
Rapid Letter	**.13**	**.24**	.09	**.15**	**.19**	**.15**	-.10	.02	.08	**.15**	.11	.08	**-.30**	**-.35**	**-.45**	**-.43**	**-.41**	**-.39**	--					
Rapid Number	**.20**	**.21**	**.16**	**.15**	**.14**	.11	-.06	.05	.08	**.14**	.10	**.12***	**-.22**	**-.29**	**-.38**	**-.38**	**-.36**	**-.31**	**.83**	--				
Rapid Alternating	**.14**	**.23**	**.14**	**.14**	**.15**	.09	-.03	.04	.06	**.18**	.06	**.13**	**-.28**	**-.33**	**-.43**	**-.40**	**-.39**	**-.36**	**.80**	**.82**	--			
Word Reading Eff	-.10	-.30	-.09	-.1	-.15	-.11	**-.15**	**-.15**	-.09	-.11	-.12	-.11	**.38**	**.49**	**.49**	**.59**	**.66**	**.63**	**-.56**	**-.50**	**-.52**	--		
Word ID: Keywords	-.08	**-.32**	-.07	-.11	**-.17**	-.14	.14	-.12	-.11	-.12	**-.17**	**-.14**	**.41**	**.55**	**.52**	**.62**	**.73**	**.65**	**-.56**	**-.49**	**-.54**	**.91**	--	
Word ID: Transfer	-.11	**-.22**	**-.12**	**-.16**	**-.14**	**-.18**	**-.20**	**-.17**	-.06	-.12	**-.15**	-.12	**.47**	**.55**	**.49**	**.62**	**.77**	**.63**	**-.40**	**-.36**	**-.37**	**.75**	**.79**	--

Confirmatory Factor Analysis

The first question of this study addresses the nature of the relationship between measures of motor control prior to intervention in young children with reading disabilities. The relationship between measures of motor functioning in a population of young children with reading disabilities was examined using confirmatory factor analysis. It was expected that three factors would be identified: repetitive, patterned, and oral movement. To confirm this factor structure of the measured motor variables, covariances between the observed measures were entered into Lisrel 8.51 using SIMPLIS syntax (Jöreskog & Sörbom, 2004). Two patterns of relationship between the measures of motor functioning and resultant latent factor construction were explored. The fit statistics are presented in Table 3. Generally, fit statistics are calculated by quantifying the correspondence between the predicted covariances and the observed covariances. For all confirmatory factor analyses and structural equation models, the fit was evaluated using multiple indices: normed fit index (NFI), nonnormedfit index (NNFI), comparative fit index (CFI),the root-mean-square error of approximation (RMSEA) and the standardized root mean squared residual (SRMR). Examinations of the chi-square difference test also were used to determine the relative increase in fit within the nested models. The chi-square statistic provides a test of the null hypothesis that the model fits the data. Models evidencing a good fit will have a chi-square that is relatively small and corresponding p values that are relatively large (i.e., close to 1.0). This statistic, however, is fallible as the chi-square can be significant even if the model represents a good fit to the data (Hu & Bentler, 1999). Researchers, therefore, seek a small chi-square rather than a nonsignificant chi-square. The other indices utilized evaluate the overall goodness-of-fit for each model. Previous research has suggested that the NFI, NNFI, and CFI indices are less likely to produce biased estimates in smaller samples or those with less than 500 participants. Values over .90 on the NFI, NNFI and CFI indicate acceptable fit. The RMSEA and the SRMR measures the residual correlation. Small values (e.g., less than .05) reflect a good fit (Kline, 1998).

Table 3. Fit indices for Confirmatory Factor Analysis models

Model	**x^2**	**x^2 diff**	**x^2 ratio**	**RMSEA**	**NFI**	**NNFI**	**CFI**	**SRMR**
CFA 1 PATAKA Repetitive Pattern	77.45 (41)	--	1.88	.055	.92	.96	.96	.057
CFA 2 PATAKA Repetitive Pattern w/ correlated errors	56.97 (39)	20.48**	1.46	.043	.95	.98	.98	.049

Two models were compared in this confirmatory factor analysis (CFA). Three factors were examined consisting of: 1) oral motor measures (PA, KA, TA, and PATAKA); 2) patterned motor movement (PANESS Finger Apposition, Hand Pronate/Suppinate, and Foot-Heel-Toe Tapping); 3) repetitive motor movement (Finger Tapping Test, PANESS Finger Tapping, Hand Tapping, and Foot Tapping). Previous research by Wolff (2002) had suggested the utility of examining the different relationships for each type of motor movement both patterned and repetitive. This research has suggested a stronger relationship to reading outcomes for measures of patterned motor movement. The results for CFA Model 1 are displayed in Table 3. This model demonstrated an adequate fit to the data. The RMSEA was close to .5 and the NFI, NNFI, and CFI were all above .9. While the SRMR was above .5 it was below .8, a typical cutoff level for behavioral sciences.

A second confirmatory factor model was run based on the desire to clarify the previous model of motor movement fluency utilizing the pattern versus repetitive motor movement factor structure. An examination of the modification indices suggested a significant drop in chi-square with the correlation of errors between the PANESS subtests of Finger tapping and Foot tapping and with the correlation of errors between the TA and PATAKA subtests of the Pataka oral movement task. As each of these measures may share measurement variance due to similar testing formats, this adjustment was theoretically and practically justified. Three factors were examined consisting of: 1) oral motor movement (PA, TA, KA, & PATAKA); 2) patterned motor movement (PANESS Finger Apposition, Hand Pronate/Suppinate, Foot-Heel-Toe Tapping); and 3) repetitive motor movement (PANESS Finger Tapping, Hand Tapping, Foot Tapping, and the Finger Tapping Test) including their correlated errors. The results of CFA Model 2 are displayed in Table 3. This model demonstrated a significantly better fit to the data than CFA 1. The chi-square difference with three degrees of freedom was greater than 6.3 (20.48; $p<.01$). In addition, all measures of goodness-of-fit drew closer to 1.0 evidencing better fit. Given both the empirical and theoretical validity of this factor structure it was retained in the examination of the relationship between motor factors to predictors of reading and word reading fluency. Factor loadings and relationships for the confirmatory factor analysis are displayed in Figure 1.

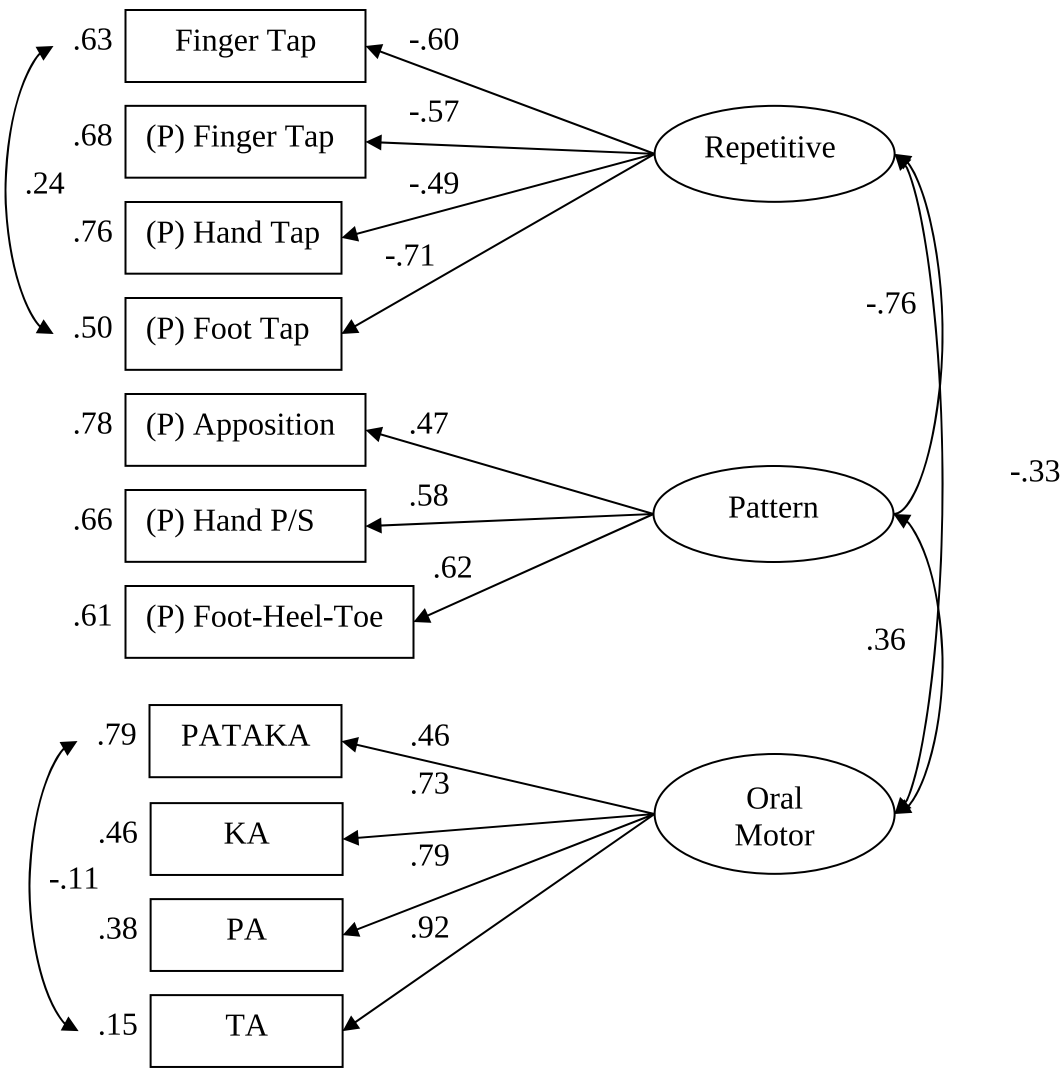

Figure 1. Confirmatory Factor Analysis with factor loadings and correlated errors. (P) denotes subtests of the PANESS.

Structural Equation Models

The second question central to this study investigates the relationship of the motor factor structure to reading related processes and word reading fluency. Model comparison was used to examine the hypothesis that motor control would be related most strongly to rapid automatized naming and reading fluency while phonological awareness would be most strongly related to reading fluency and evidence a limited association with motor control. These hypothesized associations incorporate the postulated relationship between lower-level processes related to perceptual and motoric processes and higher-level cognitive processes indexed by measures of rapid automatized naming and subsequent reading skill (Wolf & Katzir-Cohen, 2001). An alternative pattern of relationship between these lower level processes has been suggested by Wagner and colleagues (Wagner et al., 1993). In this conceptualization, phonological processing, not rapid automatized naming, represents the intermediary step between perceptual and motoric processes in their association with reading skill. Further, their findings suggest that phonological processing skill, comprised of both analysis and synthesis measures, have a direct affect on rapid automatized naming speed. These competing theoretical models were analyzed to determine which set of relationships most accurately fit these data.

Structural equation modeling (SEM) analyses were conducted using LISREL 8 Structural Equation Modeling software (Jöreskog & Sörbom, 2004). SEM analysis allows for the testing of proposed causal relationships among latent and observed variables through the use of hybrid models, which combine measurement models and path analysis models. Measurement models depict latent variables as represented by observed variables and path analysis models allow the specification of direct and indirect relationships among variables (Raudenbush & Bryk, 2002).

To evaluate the hypothesized relationships between measures of motor movement, oral motor movement, phonological processing, rapid automatized naming and word reading fluency were modeled. Kline (1998) suggests a two-step modeling procedure for evaluating a structural model with both a measurement and path analysis component. Models possessing both a structural and measurement component are referred to as hybrid structural models. Within the two-step model of evaluation, a hybrid model is first specified as a CFA measurement model. This model is evaluated as to its fit to the data. If the measurement model demonstrates a poor fit to the data the hypotheses of the research are likely incorrect, thereby negating the utility of specifying relationships within a structural model (Kline, 1998). Given an acceptable measurement model, however, the second stage of the two-step model evaluation procedure is to compare the fit of competing hybrid models (i.e., those incorporating a structural component) to one another. These models are compared through the x^2 difference test. As the name suggests, the x^2 difference statistic is simply the difference between the x^2 values of two hierarchical models. The change in degrees of freedom between the compared models represents the critical value by which to determine whether or not the two models are significantly different. A second evaluative statistic based on the chi-square is the chi-square/degrees of freedom ratio. As chi-square can be heavily influenced by sample size, this ratio aids in adjusting for this problem by taking into account the relationship between the degrees of freedom and the relationship between the hypothesized model and a null model constrained to have no relationships between the variables. Though multiple researchers suggest different cutoff levels for this ratio, a recent review suggested that values below 2.0 are frequently used in the behavioral sciences (Buhi, Goodson, & Neilands, 2007).

Measurement Model

Application of the two-step model evaluation procedure was initiated through the specification of a measurement model incorporating all observed variables. The earlier confirmatory factor analysis results in which three factors, patterned, repetitive and oral motor movement were determined was used to model the relationships between the motor measures within the extended measurement model. Two basic requirements are needed to identify a measurement model. The first is that each latent variable has at least three indicator variables. The proposed measurement model in this analysis meets this requirement. In addition, identification of a measurement model requires that each latent variable be scaled. Scaling of all latent variables in this analysis was accomplished by fixing the highest loading indicator factor loading variance to 1. The full measurement model with factor loadings with correlated errors is displayed in Figure 2. Fit indices are displayed in Table 4.

Table 4. Fit indices for Measurement Model and Hybrid Model

Model	**x^2**	**x^2 difference**	**x^2 ratio**	**RMSEA**	**NFI**	**NNFI**	**CFI**	**SRMR**
Measurement Model	413.84 (213)	--	1.94	.061	.94	.96	.97	.054
Measurement Model w/ correlated errors	359.41 (210)	54.43**	1.71	.053	.95	.97	.98	.053
Predicting RAN	360.44 (215)	53.40**	1.67	.051	.95	.97	.98	.054
Predicting Phonological Processing	359.40 (216)	.01	1.66	.051	.95	.97	.98	.057
Final Model w/Finger	364.46 (219)	5.05	1.66	.051	.95	.97	.98	.060
Final Model w/o Finger	328.56 (198)	35.90	1.65	.051	.95	.97	.98	.062

Several aspects of the measurement model are important to note. All indicator factor loadings were found to be moderate to large. Moreover, while a large correlation (r=.87) was found between the latent factor associated with phonological processing and the latent factor associated with word reading fluency, a subsequent examination of the utility of using only one phonological latent factor incorporating both latent constructs evidenced a significantly worse fit to the data (x^2 = 392.48 (210), RMSEA = .058). Given the hypothesized relationship between these two variables (i.e., one by which phonological awareness predicts word reading fluency) and the poorer fit to the data demonstrated by a model in which the two variables are constrained to be the same, the two latent constructs, phonological processing and word reading fluency were retained as separate in subsequent analyses.

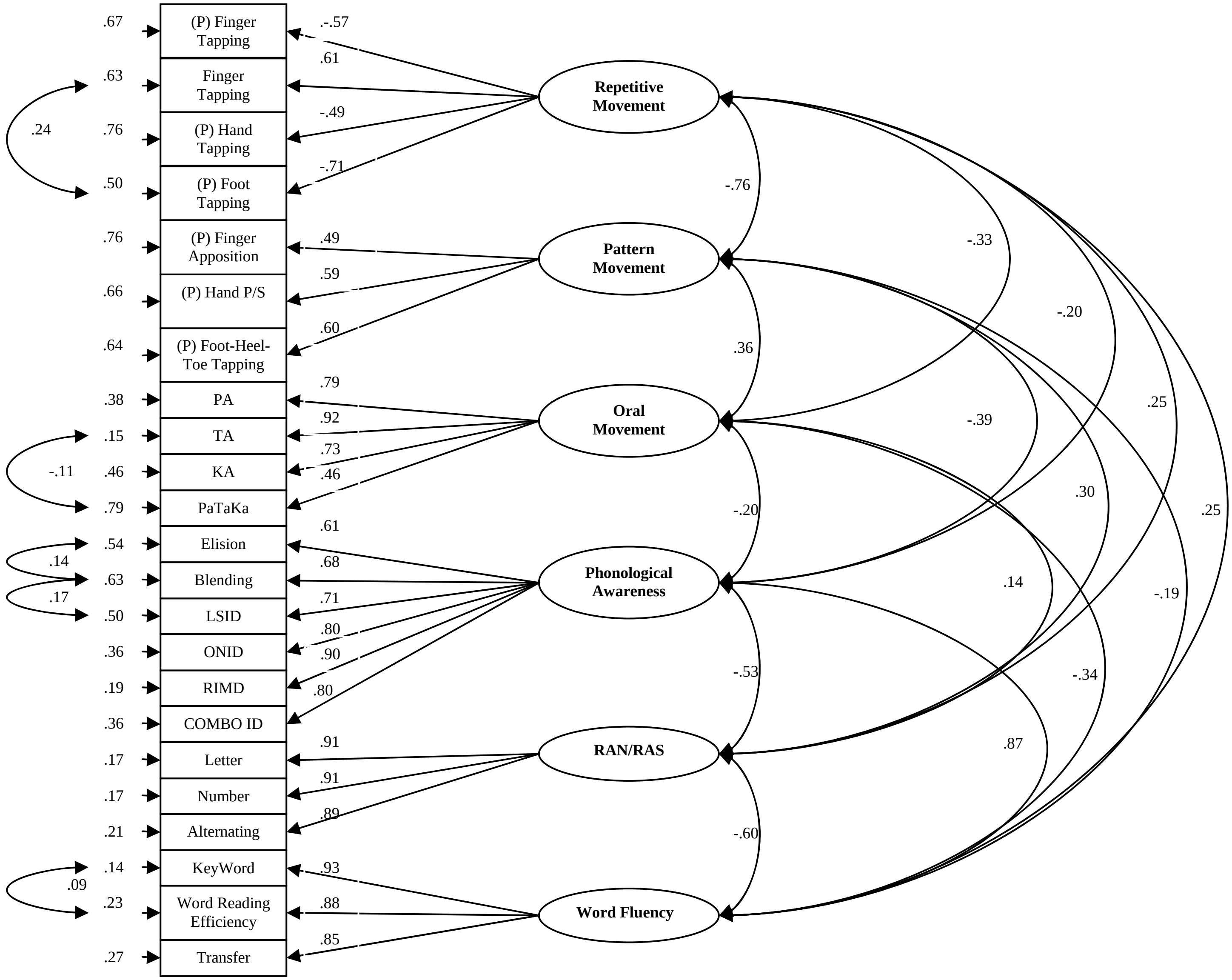

Figure 2. Measurement model with factor loadings and correlated errors

Hybrid Models

With the confirmation of a good fitting measurement, Kline (1998) suggests that the next step is to include the structural component to the model. The structural component consists of the hypothesized paths between the latent variables assumed by the researcher to represent the real-world relationships within this particular sample between the observed variables measured. The relationship between phonological awareness, rapid automatized naming, and word reading fluency has been extensively investigated in the literature (Vellutino et al., 1994; Wolf, Bowers, & Biddle, 2000). This previous research has suggested that phonological awareness and rapid automatized naming affect word reading fluency. Further, a relationship between phonological awareness and rapid automatized naming is frequently cited in the literature (Wolf & Bowers, 1999; Manis et al., 1999). As such, each of the tested models investigated the degree to which the constellation of motor fluency measures influences or interacts with the relationship between these indicators, i.e., phonological processing and rapid automatized naming, of early reading ability.

Predicting Rapid Automatized Naming

The first hypothesized model investigated the relationship between the motor measures upon the measures of word reading fluency, phonological awareness, and rapid automatized naming directly. This model is statistically equivalent to the overall measurement model discussed earlier aside from the estimation of path coefficients instead of correlations between variables. Again, the fit statistics suggest an adequate model (x^2 = 359.41 (df=210); RMSEA: .053). This full model represents all possible relationships between the latent factors of patterned, repetitive, and oral movement upon latent factors of phonological awareness, rapid automatized naming, and word reading fluency. Further, based on previous research, relationships between the latent reading factors also were incorporated. Each path coefficient can be interpreted as a beta weight from multiple regressions. Moreover, each path is assessed as to its statistical significance. By employing both of these considerations, the researcher is provided with important information in the process of specifying the best and most complete model. Within the current full model, strong relationships were found between the latent motor factor related to patterned movement and the latent factor related to phonological awareness (-.48). None of the other relationships between the latent factors of repetitive or oral motor movement were found to be significantly related to phonological awareness, rapid automatized naming, or word reading fluency. Both phonological awareness and rapid automatized naming were found to be significantly related to word reading fluency (phonological, .80; RAN -.17). Finally, phonological awareness was found to be significantly related to rapid automatized naming (-.26). The full model fit statistics are displayed in Table 4.

Predicting Phonological Processing

The second model investigated whether or not the relationship between word reading fluency and motor movement operates through the effect of rapid automatized naming on word reading fluency. As the pattern of relationships between phonological awareness, rapid automatized naming, and word reading fluency were found to be both theoretically and statistically sound, they were conserved for examination in all subsequent analyses. Further, as pattern was found to be significantly related to phonological processing, it too was conserved for subsequent model fitting procedures. The fit of the second model is displayed in Table 4. Specifically, the latent factors associated with repetitive, patterned, and oral movements were allowed to load on the latent factor associated with rapid automatized naming. Latent measures of motor fluency were not found to be significantly related to measures of rapid automatized naming. Significant path coefficients were found between patterned -> phonological awareness (-.38), phonological awareness -> rapid automatized naming (-.48), phonological awareness -> word reading fluency (.77) and rapid automatized naming -> word reading fluency (-.19). In sum, these findings provide support for the view that phonological processing represents an intermediary between lower-level processes related to motoric functioning as opposed to an intermediary step related specifically to rapid automatized naming in the concurrent prediction of word reading fluency.

Predicting Patterned Motor Movement

A third model was tested capitalizing upon the significant relationship found between phonological awareness and patterned motor movement. If reading progresses through lower level cognitive processes to higher level processes as suggested by Wolf and Katzir-Cohen (2001), what is the relationship between simpler oral and repetitive movements and more complex patterned movements when modeling word reading fluency? An examination of the residual correlation matrix from the previous model revealed that both of the latent factors for repetitive movement and oral motor movement demonstrated a moderate relationship with patterned movement. The third model capitalized on this relationship by allowing both oral motor and repetitive motor movement latent variables to predict the latent patterned movement variable. Further, patterned movement was allowed to predict phonological processing. Phonological processing was allowed to predict both rapid automatized naming and word reading fluency and rapid automatized naming was allowed to predict word reading fluency. The path from the oral movement factor to the patterned movement factor was not significant and was eliminated. The model was respecified to allow the oral movement factor to predict the repetitive movement factor. This respecification was based on the desire to capitalize on the repetitive movement requirements inherent to both sets of motor tasks. This model represented a good fit to the data. All hypothesized relationships among latent factor were significant. One caveat to the explication of these relationships, however, is warranted upon the examination of the indicator variables to the latent factor structure with the repetitive movement factor. The negative relationship between these indicators and the resultant factor, in effect, creates a negative factor whereby the subsequent associations to this factor are interpreted in the opposite direction. Simply, the combination of two negative relationships creates a positive relationship. Therefore the finding that the oral movement factor was significantly negatively related to the repetitive movement factor (-.36) should be interpreted as a positive relationship. This negative relationship indicates that longer oral movement latencies are associated with longer repetitive movement latencies. Similarly, the significant negative relationship between repetitive movement and patterned movement (-.77) indicates that longer latencies in repetitive movement are associated with longer latencies on the patterned movement variable. All other indicator to factor relationships evidenced positive associations allowing for the direct interpretation of the path coefficients without the need to 'flip' the associated path coefficient sign or direction of effects.

The negative relationship between patterned movement and phonological awareness (-.38), therefore, indicates that longer latencies for patterned movement are associated with lower scores on the phonological awareness factor. Moreover, the negative relationship between phonological awareness and rapid automatized naming (-.53) indicates that lower phonological scores are associated with longer latencies on the rapid automatized naming factor. Phonological awareness was found to have a positive significant relationship with word reading efficiency (.77) indicating that higher scores on the phonological factor are associated with more words read under time constraints for the word reading fluency factor. Finally, rapid automatized naming was found to have a negative significant relationship (-.19) to word reading fluency indicating that longer latencies on the rapid automatized naming factor were associated with fewer words read in the word reading fluency factor. This model with factor loadings and correlated errors is displayed in Figure 3. The fit indices for this model are displayed in Table 4.

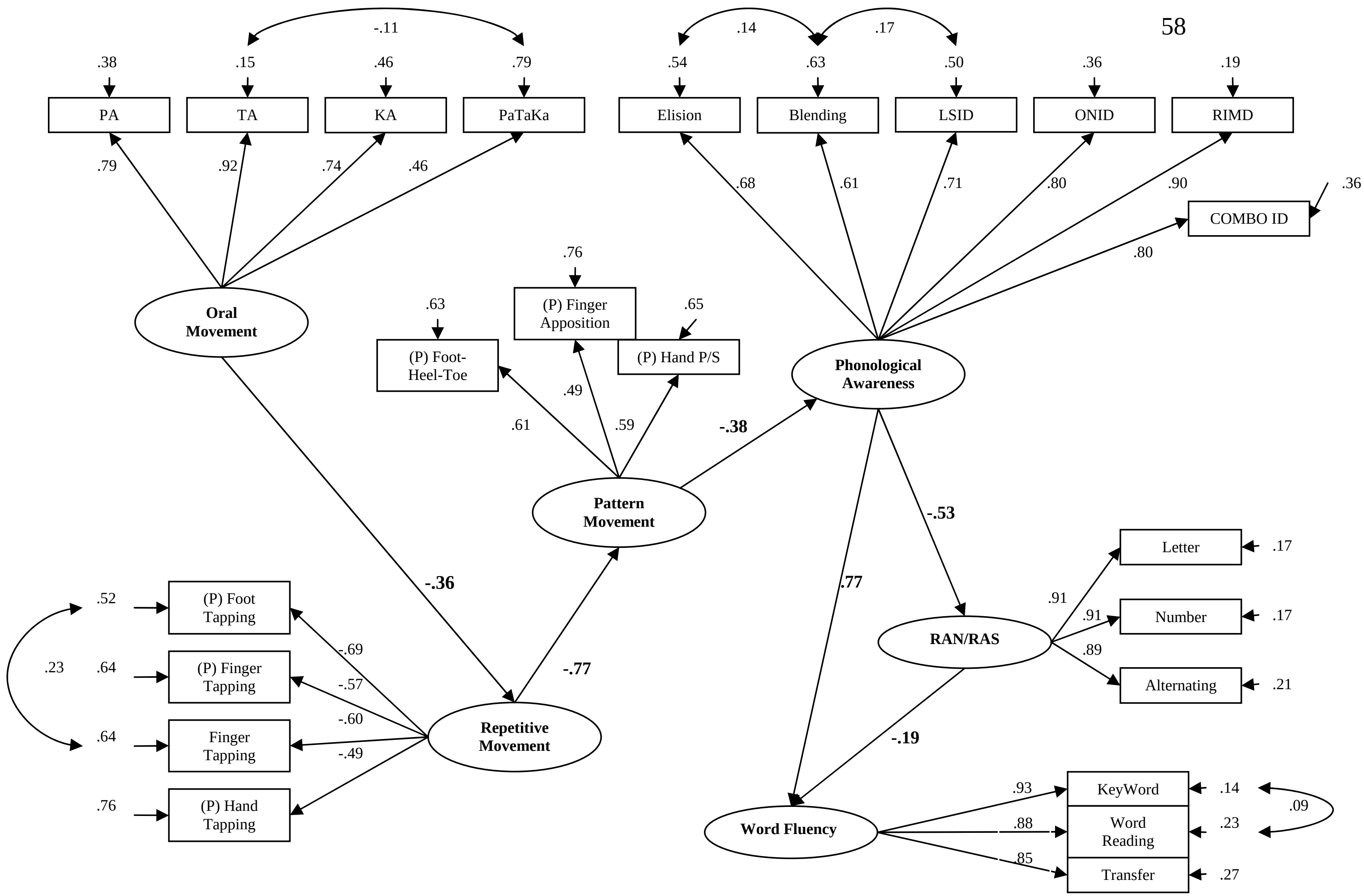

Figure 3. Final model with Finger Tapping Task

Finally, examination of the correlation matrix revealed an opposite pattern of relation between the Finger Tapping Test and the other motor measures associated with the latent factor of repetitive movement. This measure's inclusion into the latent factor was therefore tested against the integrity of the model and its internal cohesiveness. The previous model was analyzed without including the Finger Tapping Test. All other factor constructions and hypothesized path relationships were conserved in this final model. This model evidenced a significantly better fit than both the measurement model and hierarchically more complex model, suggesting that it represents the best fit to the data within both the constraints of parsimony and theory. The fit indices for this model are displayed in Table 4. The most obvious change in this model from the previous model can be found within the relationship between the latent repetitive motor factor and both the oral and patterned motor factors.

The relationship now supports a more transparent interpretation of the model structure. Oral motor movement is positively related to repetitive motor movement whereby longer latencies in the oral movement factor are related to longer latencies in the repetitive motor movement factor. In addition, the positive relationship between the repetitive motor movement factor and the patterned motor movement factor suggests that longer latencies in the repetitive factor are related to longer latencies in the patterned factor. Finally, this motor factor structure of relationship does not directly impact on single word reading fluency but instead, operates directly upon the largest predictor of word reading fluency, phonological awareness. This relationship between patterned motor movement and phonological awareness demonstrates that longer latencies required to complete particular motor patterns is predictive of lower scores on measures of phonological awareness. Succinctly then, a deficit in the rate at which motor movements are performed, consistent across three separate but related areas of movement in young children with a reading disability is predictive of the facility with phonological information can accessed, recalled, and produced in the estimation of single word reading fluency. This final model is displayed in Figure 4.

Regression Analyses

In order to further explicate the relationship between measures of motor functioning, reading related processes, and reading fluency, regression analyses were conducted. Findings from the structural equation models suggest that measures of motor functioning do not directly impact on reading fluency, but instead operate through phonological processing. Further, the lack of a significant association between measures of motor functioning and rapid automatized naming in the structural models suggests that these constructs share little variance in the prediction of reading fluency scores. Regression analyses therefore were conducted to explicate the amount of variance accounted within each construct by its modeled antecedent.

Factors related to each of the hypothesized constructs were created using Factor Analysis in SPSS 14.0. Principal axis factoring was selected as this method of analysis is preferable to principal components analysis when the intent is to define latent variables that are contributing to the common variance in a set of measured variables. This type of analysis postulates that each measured variable in a selected battery of measures is a linear function of one or more common factors and one unique factor. Common factors are unobserved latent variables that influence one or more measured variable in a battery and are presumed to account for the correlations among the measured variables. Unique factors are assumed to have two components: a specific factor component and an error of measurement component. In contrast, principal components analysis does not differentiate between common and unique variance but instead defines each measured variable as a linear function of each identified principal component (Fabrigar, Wegener, & MacCallum, 1999). As the intent of this analysis is the identification of unique factors within the measured battery of motor functioning, principal axis factoring was used in this examination of the data. Factor construction through Factor Analysis in SPSS, however, differs from latent factor construction in Lisrel structural equation modeling. As stated above, the unique factors derived through principal axis factoring incorporate both variance specific to the factor and variance related to the error of measurement for each indicator variable. Conversely, structural equation modeling allows for estimation of this error of measurement separate from the variance specific to the factor. These differences do not allow for the direct interpretation of the path coefficients from the previous structural models as the same beta weights within multiple regression based on factor scores from principal axis factoring. Further, multiple regression assumes that each variable is measured without error. This differs from structural equation modeling in that the error of measurement associated with each indicator variable for a latent construct is specifically modeled apart from that part of the variance which is uniquely shared with the other indicator variables in the construction of the latent variable. This analysis does, however, provide an estimate of the total effect of each variable controlling for all other predictor variables for reading fluency. Specifically, an examination of the partial correlation coefficients reveals the unique variance contributed by each predictor variable after controlling for all other predictors. The results from these regression analyses are displayed in Table 5.

Table 5. Regressions to estimate effects of factors on reading fluency

Criterion	Predictor	Factor Regression Coefficients: Unstandardized	Factor Regression Coefficients: Standardized	*Part Correlation*	R^2	$(1-R^2)$
Repetitive	Oral	.17 (.05)	.21**	.21	.04**	.96
Patterned	Oral	.14 (.05)	.17**	.17	.23**	.77
	Repetitive	.40 (.06)	.41**	.42		
Phonological	Oral	-.11 (.06)	-.11	-.11	.09**	.91
	Repetitive	-.08 (.08)	-.06	-.06		
	Patterned	-.26 (.09)	-.21**	-.19		
Rapid Naming	Oral	.02 (.06)	.02	.02	.24**	.76
	Repetitive	.13 (.08)	.11	.10		
	Patterned	.07 (.08)	.05	.05		
	Phonological	-.44 (.06)	-.44**	-.42		
Fluency	Oral	-.02 (.04)	-.02	-.02	.61**	.39
	Repetitive	.05 (.06)	.04	.04		
	Patterned	-.04 (.06)	-.03	-.03		
	Phonological	.63 (.05)	.61**	.53		
	Rapid Naming	-.28 (.05)	-.28**	-.24		

Each criterion variable is predicted by the preceding independent variable as outlined within the structural model specified above. Both oral and repetitive movements were found to contribute significant variance to the prediction of patterned movement. These two factors, however, were not found to contribute significant variance to the prediction of either reading related processes or reading fluency. Patterned movement was found to contribute significant variance to the prediction of phonological processing, but was not found to be significantly related to either rapid automatized naming or reading fluency.

Finally, the last two columns reflect the amount of variance accounted for and amount of variance left unexplained in the criterion variable after the inclusion of the predictor variable. This number can be interpreted as a percentage. For the first regression, oral movement accounts for only 4% of the variance in repetitive motor movements. Both repetitive and oral motor fluency accounted for 23% of the variance in patterned movement. Patterned, repetitive, and oral fluency accounted for only 9% of the variance in phonological processing, though only patterned fluency was a significant predictor. Twenty-four percent of the variance in rapid automatized naming was accounted for by phonological processing, and patterned, repetitive and oral movement, though only phonological processing was significant. For reading fluency, the confluence of all included observed variables accounted for 61% of the variance, but the only significant predictors were phonological processing and rapid automatized naming.

The influence of the motor fluency factors to reading fluency, therefore, is limited to its predictive relationship with phonological processing. Of the motor fluency measures, only patterned movement was found to significantly predict phonological processing. Further, only phonological awareness and rapid automatized naming were found to be significant predictors of reading fluency.

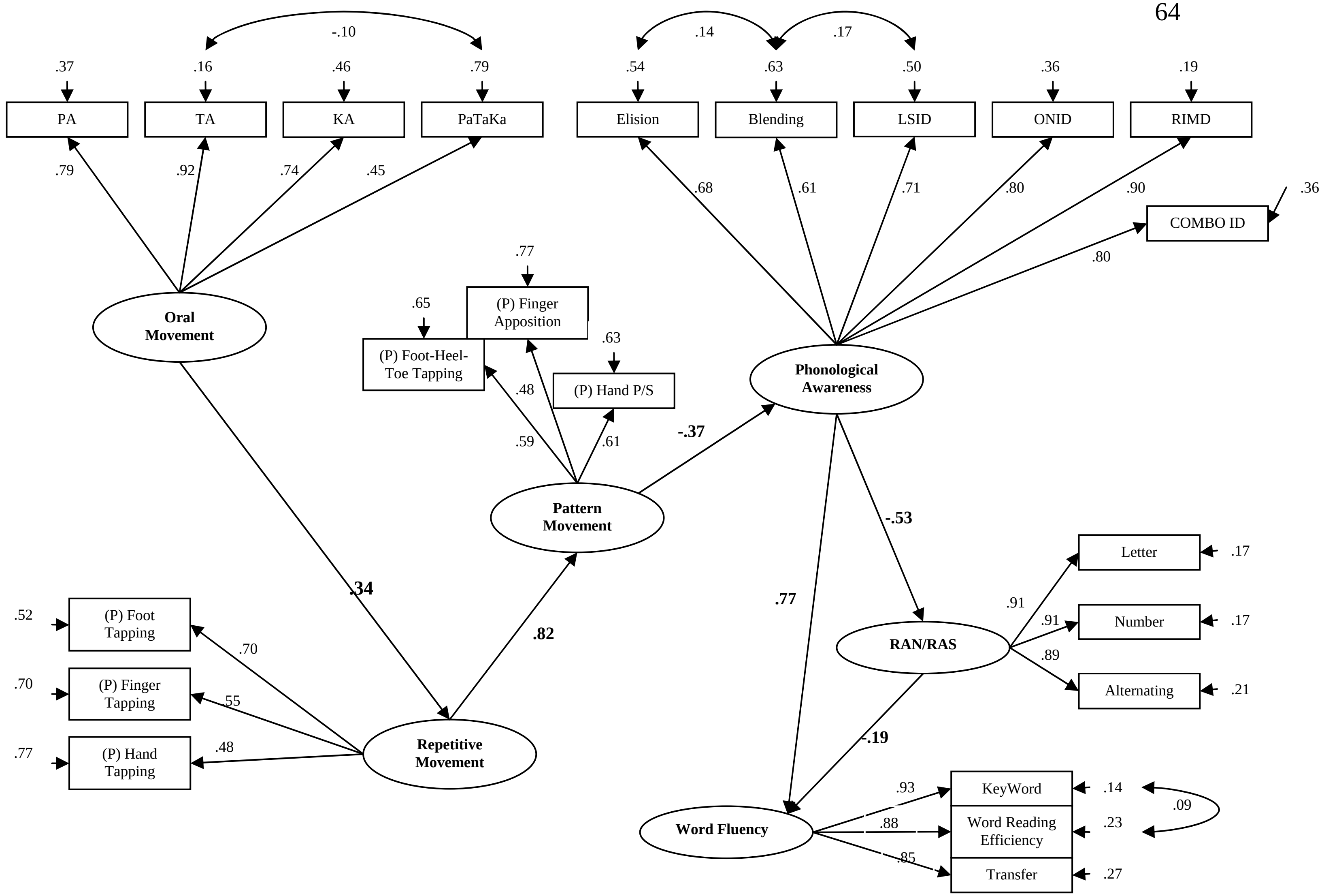

Figure 4. Final model without Finger Tapping Task

Discussion

Consistent with previous research, the present study demonstrated a reliable relation between reading and reading related processes and motor movement fluency (Nicolson & Fawcett, 1999; Wolff, 2002). Specifically, measures of patterned motor movement were found to predict facility with phonological processing. Measures of repetitive and oral movement were not directly related to measures of reading or reading related processes but did evidence a predictive relationship with patterned motor movement. These findings are displayed in Table 6.

Table 6. *Major findings in relation to relevant questions and hypotheses*

Question	Hypothesis	Findings
What is the relationship between measures of motor functioning in young children with a reading disability?	Three areas of motor functioning will be established: oral, repetitive, and patterned movement	**Confirmed**; Confirmatory factor analysis revealed three related but separate constructs within the battery of motor functioning: oral motor, repetitive, and patterned
How does this factor structure of motor functioning relate to reading fluency in young children with a reading disability?	**1.** Motor functioning will directly relate to reading fluency **2.** Motor functioning will directly relate to rapid automatized naming **3.** Motor functioning will directly relate to phonological processing **4.** Simple motor tasks will relate to more complex motor tasks	**1. & 2. Rejected**; Motor functioning did not significantly relate directly to either rapid automatized naming or reading fluency **3. Partially confirmed**; Patterned motor functioning was highly predictive of phonological processing which was highly predictive of reading fluency **4. Confirmed**; Oral motor movement was significantly related to repetitive motor, while repetitive motor movement was significantly related to patterned motor movement

Clearly, patterned motor movement does not cause phonological processing. Rather, these results suggest that some skill, namely temporal processing, underlies both patterned motor movement and phonological processing. The act of reading is a process that must be executed under time delimited conditions (Breznitz & Meyler, 2003). Under one conceptualization, timing within the reading process can be measured by the actual rate at which a passage can be read and understood. This level of measurement represents an observable outcome easily linked to child's reading development and, as such, is frequently employed in studies of reading (Fuchs et al., 2001). Another view of timing within the reading process, however, suggests that temporality of the reading process is paramount within all aspects of reading (Wolf & Katzir-Cohen, 2001). In other words, the time required to read and understand a passage of text represents only one point in the process in which linguistic and symbolic information must be accessed, associated, and produced. Within this conceptualization, then, deficits related to the temporal processing of motor, linguistic, and symbolic information may not only relate to the more observable outcome of impaired reading fluency but also serve as predictors of this outcome. Using indicators of motor fluency related to repetitive, pattern, and oral movement, this study supports the broader view of temporal processing in the reading process. The results suggest that the rate with which a child with a reading disability can produce a motor based pattern using either their hands or feet is moderately predictive of the facility with which the child can access, associate, and reproduce phonetic information. Phonological processing has been consistently linked in the literature of reading outcomes and represents the most highly researched and hypothesized source of deficit for children with a reading disability (Adams, 1990). This study suggests that this factor is influenced by lower-level processes that can be accessed and measured through measures of motor fluency. The link between these two conceptually disparate areas of functioning can be found in lower-level deficits in temporal processing. Stated another way, decoding skills required for word reading are dependent on phonological representations. Previous research has suggested that the precision of these phonological representations is influenced by the temporal contiguity with which they are perceived (Adams, 1990; Booth et al., 1999; Hebb, 1949). To the extent that both phonological representations and skilled motor movement share the requirement of coordinating a variety of muscles and perceptual abilities, less fluid manual coordination acts as a signature for less fluid productions, which consequently are less supportive of fluent decoding (Carello, LeVasseur, & Schmidt, 2002).

Hypothesis One

The first hypothesis of this study examined the construction of latent factors within a larger battery of measures of motor functioning. Specifically, the first hypothesis addresses the question: What is the relationship between different measures of motor fluency that assess disparate areas of oral, patterned, and repetitive motor movement functioning? The findings of this study suggest that a three factor solution corresponding to oral, repetitive, and patterned motor movement represents an excellent fit to the data collected from young children with a reading disability. This three factor construction adds to the current literature through the addition of the oral movement factor as a construct separate from both repetitive and patterned motor movement. Additionally, these findings support earlier research by Wolff (2002) suggesting the investigation of patterned and repetitive movement as related yet separate constructs of motor functioning. The interpretability of these findings, however, must be approached in light of several caveats. While repetitive and patterned movements were highly correlated, a single factor motor structure did not display a significantly better estimate of the raw covariance matrix. Moreover, the Finger Tapping Task evidenced an opposite pattern of relationship with the repetitive movement factor in relation to the other indicator variables. This difference was most likely due to a difference in test construction. The Finger Tapping Task assesses the amount of time required to tap a particular cadence 10 times. The score is then represented as a rate, or the time required to complete each movement. In contrast, the PANESS records the total time required to complete 20 repetitions of each repetitive or patterned movement. The PANESS subtest scores were converted into rate scores (i.e., the overall time was divided by the number of repetitions) and utilized in a subsequent correlational analysis. The pattern of relationship between the PANESS subtests and the Finger Tapping Test did not change (i.e., the relation of the Finger Tapping Test to the other indicators of the latent construct of repetitive movement remained negative). While future work should continue to examine the differences between these measures of motor fluency that may account for this difference in relationship, the results of this study, with regard to the associations between the latent constructs, did not change significantly with the exclusion of the Finger Tapping Task. These findings suggest the utility of examining a multiple factor structure within the PANESS battery through the distinguishing of those tasks related to repetitive and patterned motor movement in the prediction of phonological awareness.

Surprisingly, the oral movement factor was not directly related to phonological awareness. Previous work has suggested that oral diadochokinesis is impaired in children (Wolff et al., 1990a) and adults (Tiffany, 1980) with reading disabilities. Though Tiffany (1980) did not find that oral diadochokinetic rate related to the rate of articulatory gesture, other researchers have suggested that this measure represents an observable endpoint in motor speech (McPhillips & Sheehy, 2004). In other words, the complexity of motor speech programming, which in adults requires the coordination of 140,000 neuromuscular events per second when speaking at an average rate of 14 phonemes per second, rests upon the lower level motoric and cognitive skills inherent to structures related to sequencing, control, and inhibition (Fawcett & Nicolson, 2002). Fawcett and Nicolson (2002) examined whether or not children with dyslexia could be identified from a group of children without dyslexia on the basis of differences in articulatory rate as indexed by a task similar to the PATAKA task. This task employed both monosyllabic and multisyllabic repetitions. Their results support the ability of such articulatory tasks to differentiate children with and without dyslexia. Further, their results suggest that only monosyllabic repetitions were significant in differentiating between children with and without reading disabilities. In their research, the multisyllabic repetition rate was only minimally associated with the monosyllabic repetition, a finding supported by this analysis. In addition, their study did not directly assess the degree to which oral diadochokinesis predicts reading or reading related processes. Rather, this study sought to extend the evidence of a consistent deficit within the heterogeneous population of children with a reading disability for oral diadochokinetic rate. The analysis within the current study represents the first known attempt to model the unique variance within the relationship between an oral motor movement factor and aspects of the reading process. Instead of a direct relationship, these findings suggest that deficits of oral diadochokinetic rate may indicate an overall deficit related to temporal processing observable within other motor areas. Finally, multisyllabic repetition was only minimally assessed in both the Fawcett and Nicolson (2002) study and in this analysis (e.g., only one subtest to assess multisyllabic repetition versus three subtests for monosyllabic). Conceptually, the multisyllabic repetition rate better approximates the type of articulatory gesture programming required for normal speech. It is therefore important for future examinations of articulatory speed for children with reading disabilities to employ multiple measures of multisyllabic diadochokinetic rate in order to clarify the relationship between repetition rate and any subsequent relationship to reading and reading fluency.

Hypothesis Two

The second hypothesis of this analysis examined whether or not the three-factor motor structure relates to reading fluency either independently or through other reading related factors. Generally, three theoretical models were examined: 1) measures of motor functioning were directly related to reading fluency and to reading related processes; 2) that measures of motor functioning operated on reading fluency only through rapid automatized naming; and 3) that measures of motor functioning operated on reading fluency only through phonological processing. The findings of this study suggest that motor functioning is not related directly to reading fluency or rapid automatized naming but instead indirectly through measures of phonological processing. Further, these findings support the conceptualization of phonological processing as the intermediary step for the association of lower-level cognitive processes related to motor functioning (Torgesen et al., 1994) as opposed to the conceptualization of rapid automatized naming as the intermediary step (Wolf & Bowers, 2001). Moreover, the best fitting model suggests that only patterned motor movement is directly related to phonological processing. This outcome supports earlier work by Wolff (1999) in which evidence of deficient processing in complex motor tasks, but not simple repetitive motor tasks, was related to poorer reading skills in a small sample of adolescent boys with dyslexia. Further, Wolff utilized more complex tasks in which children were required to follow a pattern a different rates. These more complex tasks would require more online processing. Wolff (2002) suggests that the concept of temporal processing is too broad and inconsistently defined throughout the literature. He suggests that corroborating evidence of temporal deficits in children with reading disabilities ought to be sought within the components of temporality, such as rate. The design of the current study allowed the child to set his or her own rate at which he or she performed the motor movements. This differed from the tasks utilized by Wolff and colleagues in that they highlight the utility of observable deficits of rate within temporal processing even at comfortable or naturalistic expressions of motor fluency.

Effective phonological processing within the tasks comprising the phonological processing factor requires that the child have precise phonological representations that can be accessed and executed effectively. The precision of the phonological patterns, however, requires that they be formed and strengthened within a short temporal period of time in as suggested by Hebb (1949). The negative relationship to patterned motor movement then suggests that a temporal processing factor related to pattern recognition and execution can be found within motor functioning as a lower-cognitive process and related to phonological processing as a higher cognitive process both utilizing temporally associated relationships. Further, the moderate relationship capitalizing on uniquely shared variance suggests that multiple unmeasured factors are related to efficient phonological processing. Yet, as most studies of phonological processing do not incorporate measures of motor functioning in their examination of phonological processing development, the inclusion of such factors may represent a more holistic approach to understanding the etiology of phonological processing development.

The pattern of relationship between the measures of reading related factors to reading fluency was consistent with the findings of multiple studies examining phonological processing and rapid automatized naming in relation to reading development (Manis et al., 1997; Wagner et al., 1994). Phonological awareness was found to be significantly related to both the reading fluency factor and rapid automatized naming. The relationship to rapid automatized naming evidenced a significant negative relationship such that greater phonological processing skill was related to shorter rapid automatized naming latencies. This finding adds further support to the theory that effective phonological representation is utilized within rapid automatized naming such that stronger representations for phonologically-based relationships are integral to rapid access and execution of the sound-symbol relationship within the rapid automatized naming tasks (Wagner et al., 1993). The factor related to phonological processing also was found to have a significant positive relationship to the factor related to reading fluency. This relationship can be interpreted such that better phonological processing skills are related to reading more single words within a specific time limitation. Efficient and precise representations of phonological information aids in the speeded recall of the phonological information needed to decode and express the real words comprising the reading fluency measures. Finally, the rapid automatized naming factor was found to be negatively significantly related to the reading fluency factor. This finding can be interpreted as longer latencies on the rapid automatized naming factor are related to fewer words read under time delimited conditions within the reading fluency factor. The negative relationship between both phonological processing and rapid automatized naming confirms previous research examining the contribution of rapid automatized naming to reading wherein greater rapid automatized naming skill evidenced by shorter latencies is related to greater reading skill evidenced by more words read (Bowers & Wolf, 1993; Savage & Frederickson, 2005).

Finally, a relationship between the measures of motor fluency was demonstrated. Namely, oral movement predicted repetitive movement and patterned movement scores. The results of the regression analyses indicate that the oral movement factor is positively related to both repetitive and patterned movement. Further, this relationship remains significant even after the inclusion of the repetitive movement factor. One explanation for this arises from the inclusion of a multisyllabic subtest within the oral movement factor that may account for the relationship. The multisyllabic task requires the replication of a complex pattern of articulatory gestures. Though motorically and conceptually different from the movement patterns enacted in the PANESS subtests, future work should examine possible connections between more complex articulatory gesture combinations and patterned movements.

Limitations

This examination of motor fluency and its relationship to reading fluency represents the first attempt to model their common unique variance. Further, this study differs from the majority of the literature in the scope of the measures utilized by including three separate factors related to motor movement and a large cross-gendered sample of non-clinically referred participants. This study, however, did not control differences in motor fluency related to age. This was not controlled for in part due to the implementation of the test battery utilized by the larger study from which this analysis was drawn. Measures not assumed to be influenced by exposure to reading intervention, such as those related to motor fluency, were collected across the first two timepoints as opposed to the collection of all other reading related measures that were collected prior to direct instruction in a reading intervention setting. Within 35 hours of instruction, however, all measures of motor fluency had been collected. This represents a potential seven week difference in the timepoints at which the measured variables were collected. This does not represent a significant portion of time in motor development (McPhillips & Sheehy, 2004) but could for phonological skills within the context of intervention (Torgesen, 2005). Previous research has suggested that deficits related to temporal processing in adults with dyslexia can still be indexed through deficits related to motor movements (Wolff, Michel, & Ovrut 1990a; Meyler & Breznitz, 2005). Therefore, while it is unlikely that this lag in test administration had a demonstrable effect on the pattern of observed relationship it should be endeavored in the future to establish a base rate for motor movement tasks prior to reading instruction given the significant relationship between patterned movement and phonological processing skills.

Moreover, this study did not find a significant relationship between measures of motor fluency and rapid automatized naming. Previous theoretical conceptualizations of rapid automatized naming by Wolf and colleagues have specifically suggested that motoric processes are related to RAN development. The results of this study do not confirm these findings. This study utilized only measures of RAN related to graphonumeric stimuli versus the inclusion of subtests related to picture or color naming which could account for the difference. Conversely, Savage and Frederickson (2005) found that the naming of digits evidenced a highly specific relationship to text reading speed over the naming of pictures. These findings suggest the need to examine a more extensive battery of RAN tasks in fully estimating the relationship of RAN to motor fluency tasks.

This study did not directly assess constraints of the cerebellar deficit theory of dyslexia (Nicolson & Fawcett, 2001). Previous research on this theory has incorporated various measures of motor fluency related to postural stability and muscle tone in addition to measures related to speed of execution (e.g., Fawcett et al., 2001). To the extent, however that this theory refers to deficits of temporal processing that bear a significant relationship to the development of reading skills the findings of the current study are supportive. The current study, however, cannot address the location of impairment within the brain or the overall state of automatization in children with a reading disability, supporting only the interconnected nature of these motoric processes to reading development.

Implications for Children at risk for Reading Disabilities

Deficits related to motor fluency may provide a potential marker observable in young children at an early age in development. Though replete with difficulties in operationalizing the exact contributions of motor functioning to later cognitive development, the findings of this study, in conjunction with previous research, suggest that motor functioning may represent an ecologically valid yet simple assessment tool for identifying children who may later evidence difficulties with learning to read. Further, these deficits in motor functioning may be present at an early age and remain stable throughout childhood and adulthood (McPhillips & Sheehy, 2004; Nicolson & Fawcett, 2001; Wolff et al., 1990b). Through the early detection of motor fluency problems at a young age, teachers and other professionals can be signaled as to the potential for future deficits in phonological awareness and later reading development. Early identification and intervention have been consistently cited as the best means by which to encourage adequate reading progress for children at risk for developing reading disabilities (Lyon, 2002; Torgesen, 2005)

Motor functioning represents an empirically valid addition to the assessment of children suspected to evidence reading failure and possible disability. Conversely, the utility of remediating reading disabilities with the addition of specific exercise and motor based interventions, however, has found less support in the literature. Blythe (2005) incorporated a 10-15 minute daily exercise routine for a group of 34 elementary school students for one academic year. In comparison to an age matched control group, the children receiving the additional exercise regiment demonstrated significant reductions in signs of problems with balance, coordination, and reflexes. Moreover, this experimental group demonstrated significant improvements in speed of processing for visual and auditory information as well as increases in visual associative processing. These areas of processing are consistently found to be areas of deficient processing for children with reading disabilities and represent the core components to theories of dyslexia centering on a magnocellular explanation (Stein & Walsh, 1997). Significant effects of this exercise regiment for improved reading, however, were not examined in this research.

Reynolds, Nicolson, and Hambly (2003) investigated the added value of a home based exercise program, enacted in addition to regular classroom based instruction in reading, to the remediation of reading difficulties in a highly heterogeneous group of junior high school students. Their hypothesis was that this additional training in cerebellar/vestibular and eye movement fluency would show positive effects both for motor functioning in the experimental groups and that these effects would be evident through more efficient processing for the visual and auditory stimuli within the reading process. They found that the addition of a home exercise program for their experimental group translated into greater gains in motor fluency and demonstrated transfer effects into improved cognitive functioning for reading related processes. Further, Reynolds and Nicolson (2007), in a follow up study, found that those participants enrolled in the experimental exercise program continued to evidence higher reading related scores than those participants not enrolled in the exercise program. They attribute these differences to the efforts of the early intervention on motor functioning to aid in ameliorating the deficits in temporal processing thought to be subsumed under cerebellar control. The interpretation and efficacy of these studies, however, has been consistently questioned by other dyslexia researchers. Rack, Snowling, Hulme, and Gibbs (2007) identified major methodological fallacies within both reports, such as a lack of random assignment, the addition of the exercise-based intervention to the control group after the initial study but before the follow up, and extreme baseline differences within the heterogeneous group of junior high school students that incorporated participants evidencing skill in reading both significantly below and significantly above an average level of skill. Further, after examining intervening timepoints between the pre and post assessment utilized in the follow up study, though not reported and accessed only through direct communication with the researchers, Rack and colleagues did not find that the experimental group made significantly more gains on measures of literacy attainment than children who did receive the intervention. Essentially, these commentators suggest that the methodological problems within the construction of this study aid only in further confusing the possible relationship between interventions designed to address motor functioning and ameliorate the deficits for children with reading disabilities. In his review of the literature on automaticity and motor functioning, Savage (2004) suggests that more rigorous studies of intervention efforts directed at motor functioning are needed that both include a control group and utilize empirically validated measures of motor functioning in order to explicate a possible reciprocal relationship to reading development. Moreover, a longitudinal examination of motor functioning change in response to phonologically based instruction has yet to be undertaken (Savage, 2004). In order for the association between motor functioning and reading ability to evidence any measure of predictive power in the long term development of reading skill for children with dyslexia both types of research (i.e., intervention and longitudinal designs) will need to be conducted with specific regard as to the concomitant methodological difficulties with associating traditionally disparate areas of functioning (e.g., reading and motor fluency) over time.

Children with reading disabilities represent a highly heterogeneous group. As such, the model suggested by these findings should be investigated as to its applicability across relevant subgroups. For example, the majority of the early work on motor fluency and reading disabilities has focused heavily on the relationship in young male readers (Wolff et al., 1990b; Wolff, 2002) and adolescents (Fawcett & Nicolson, 2001; Fawcett & Nicolson, 2002). The inclusion of both boys and girls the current work suggests the utility of examining motor fluency measures in a broad range of readers with impairments but does not preclude the possibility that the structure of the relationships may change as a function of defining the subgroups in question. Specifically, research should attempt to test this model across gender. Previous research has suggested that though males are more likely to develop a reading disability, females with reading disabilities may evidence a different pattern of relationship between reading predictors. Further, though maturational differences have been found to be minimal in previous research on motor functioning in relation to reading disability, these studies did not attempt to address the specific contributions of motor skill to reading fluency or directly upon reading related processes. In addition, previous research has suggested that deficits of motor control are not found in all children with a reading disability. Wolff (1999) and Waber et al. (2002) reported that motor fluency deficits characterized only half of the sample. More importantly, however, these deficits were found only for those participants evidencing the lowest phonological awareness skills. Future research should investigate this model within a sample of children with a reading disability demonstrating average phonological skill, but poor reading achievement to determine the possible differences in the structure of the relationship between phonological awareness and motor fluency.

Finally, the majority of research focusing on the possible contribution of deficits in motor fluency to aspects of the reading process has primarily utilized samples of older children with established reading difficulties (Nicolson & Fawcett, 2001; Wolff, 2002). As a result, little is known as to the relationship between motor fluency and reading development in children with typical reading development. Future research should investigate the degree to which aspects of reading related development, such as phonological awareness, are impacted by motor fluency development in children demonstrating typical reading development.

Conclusion

Children with reading disabilities evidence concurrent and related deficits in motor fluency related to areas of oral, repetitive, and patterned movement and the reading related process of phonological awareness. This sample of children demonstrated moderate impairment across several measures of motor fluency. Patterned movement represented a significant predictor of facility with phonologically based information which in turn was highly predictive of single word reading efficiency. This connection between measures of motor fluency and phonological awareness may operate through a shared reliance on temporal processing skill. Though measures of motor fluency did not directly predict single word reading efficiency these measures may constitute a fruitful addition to an early reading disability screening battery and provide further insight into the development of a significant reading related process, phonological awareness.

References

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

Archer, A., & Gleason, M. (1991). *Skills for school success*. North Billerica, MA: Curriculum Associates, Inc.

Aro, M., & Wimmer, H. (2003). Learning to read: English in to six more regular orthographies. *Applied Psycholinguistics, 24,* 621-635.

Baddeley, A., Gathercole, S., & Papagano, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158-173.

Blachman, B. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first grade reading achievement. *Journal of Educational Psychology, 76,* 610-622.

Blythe, S. G. (2005). Releasing educational potential through movement: A summary of individual studies carried out using the INPP test battery and developmental exercise programme for use in schools with children with special needs. *Child Care in Practice, 11*, 415-432.

Booth, J. R., Perfetti, C. A., & MacWhinney, B. (1999). Quick, automatic, and general activation of orthographic and phonological representations in young readers. *Developmental Psychology, 35*, 3-19.

Bornstein, R.A. (1985). Normative data on selected neuropsychological measures from a nonclinical sample. *Journal of Clinical Psychology, 37,* 849-851.

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

Bowers, P. G., Sunseth, K., & Golden, J. (1999). The route between rapid naming and the reading process. *Scientific Studies of Reading, 3,* 31-53.

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

Breznitz, Z. (2001). The determinants of reading fluency: A comparison of dyslexic and average readers. In M. Wolf (Ed.), *Dyslexia, fluency, and the brain* (pp. 245-276), Cambridge, MA: York Press

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

Bruck, M. (1992). Outcomes of adults with childhood histories of dyslexia. In C. Hulme & J. R. Malatesha (Eds.), *Reading and spelling: Development and disorders* (pp. 179-200), Hillsdale, NJ: Lawrence Erlbaum Associates.

Buhi, E. R., Goodson, P., & Neilands, T. B. (2007). Structural equation modeling: A primer for health behavior researchers. *American Journal of Health Behavior, 31*, 74-85.

Carello, C., LeVasseur, V. M., & Schmidt, R. C. (2002). Movement sequencing and phonological fluency in (putatively) nonimpaired readers. *Psychological Science, 13*, 375-379.

Catts, H. W., Adolf, S. M., Hogan, T. P., & Weismer, S. E. (2005). Are specific language impairment and dyslexia distinct disorders. *Journal of Speech, Language, and Hearing Research, 48,* 1378-1396.

Denckla, M. B. (1972). Color naming deficits in dyslexic boys. *Cortex, 8*, 164-176.

Denckla, M. B., & Cutting, L. E. (1999). History and significance of rapid automatized naming. *Annals of Dyslexia, 49*, 29-42.

Denckla, M. B., & Rudel, R. G. (1974). Rapid ‘automatized’ naming of pictured objects, colors, letters, and numbers by normal children. *Cortex, 10*, 186-202.

Denckla, M. B., & Rudel, R. G. (1976a). Naming of objects by dyslexic and other learning disabled children. *Brain and Language, 3,* 1-15.

Denckla, M. B., & Rudel, R. G. (1976b). Rapid automatized naming (R. A. N.): Dyslexia differentiated from other learning disabilities. *Neruopsychologia*, *14*, 471-479.

Durunoglu, A. Y., Nagy, W. E., & Hancin-Bhatt, B. J (1993). Cross-language transfer of phonological awareness. *Journal of Educational Psychology, 85,* 453-465.

Engelmann, S., & Brunner, E. C. (1988). *Reading mastery I/II fast cycle, teachers guide*. Chicago: Science Research Associates.

Fabrigar, L. R., Wegener, D., & MacCallum, R. C. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychological Methods, 4*, 272-299.

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. (1999). Performance of dyslexic children on cerebellar and cognitive tests. *Journal of Motor Behavior, 31*, 68-78.

Fawcett, A. J., & Nicolson, R. I. (2002). Children with dyslexia are slow to articulate a single speech gesture. *Dyslexia, 8*, 189-203.

Fawcett, A. J., & Nicolson, R. I & Maclagan, F. (2001). Cerebellar test differentiate between groups of poor readers with and without IQ discrepancy. *Journal of Learning Disabilities, 34*, 119-135.

Fletcher, S. G. (1972). Time-by-count measurement of diadochokinetic syllable rate. *Journal of Speech and Hearing Research, 15*, 763-770.

Fraisse, P. (1982). Rhythm and tempo. In: D. Deutsch (Ed.), *The psychology of music* (pp. 148-190). New York: Academic Press.

Fuchs, L. S., Fuchs, D., Hosp, M. K., & Jenkins, J. R. (2001). Oral reading fluency as an indicator of reading competence: A theoretical, empirical, and historical analysis. *Scientific Studies of Reading, 5*, 239-256.

Fulbright, R. K., Jenner, A. R., Mencel, W. E., Pugh, K. R., Shaywitz, B. A., Shaywitz, S. E., Frost, S. J., Skudlarski, P., Constable, R. T., Lacadie, C. M., Marchione, K. E., & Gore, J. C. (1999). The cerebellums role in reading: A functional MRI study. *American Journal of Neuroradiology, 20*, 1925-1930.

Galaburda, A. M., Sherman, G. P., Rosen, G. D., Aboitiz, F., & Geschwind, N. (1985). Four consecutive patients with cortical anomalies. *Annals of Neurology, 18*, 222-233.

Gaskins, I. W., Downer, M.A., & Gaskins, R. W. (1986). Introduction to the Benchmark school word identification/vocabulary development program. Media, PA: Benchmark.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114*, 345-362.

Hebb, D. O. (1949). *The organization of behavior: A neuropsychological theory*. Oxford, England: Wiley.

Helevang, E., & Hugdahl, K. (2003). Imparired visual attention in children with dyslexia. *Journal of Learning Disabilities, 36*, 68-74.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling, 6*, 1-55.

Iversen, S., Berg, K., & Ellertsen, B. (2005). Motor coordination difficulties in a municipality group and in a clinical sample of poor readers. *Dyslexia: An International Journal of Research and Practice*, *11*, 217-231.

Jöreskog, K., & Sörbom, D. (1993). *Lisrel 8: Structural equation modeling with SIMPLIS command language.* Chicago, IL: Scientific Software International.

Jöreskog, K., & Sörbom, D. (2004). *Lisrel 8.71*. Chicago, IL: Scientific Software International.

Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology, 30*, 949-954.

Kaufman, A. S., & Kaufman, N. L. (1990). Kaufman brief intelligence test. Circle Pines, MN: American Guidance Services.

Kline, R. B. (1998). *Principles and Practice of Structural Equation Modeling.* New York: The Guilford Press.

Klonoff, H., & Low, M. (1974). Disordered brain function in young children and early adolescents: Neuropsychological and electroencephalographic correlates. In R. M. Reitan and L. A. Davidson (Eds.), *Clinical neuropsychology: Current status and applications*. John Wiley & Sons: New York (pp. 121-178).

Lefton, L. A., Nagle, R. J., & Johnson, G. (1979). Eye movements dynamics of good and poor readers: Then and now. *Journal of Reading Behavior, 11*, 319-328.

Llinas, R. (1993). Is dyslexia a dyschonia? In P. Tallal, A. M. Galaburda, Llinas, R. R., & C. von Euler (Eds.), Temporal information processing in the nervous system: Special reference to dyslexia and dysphasia. New York Academy of Sciences: New York (pp. 48-56).

Lovegrove, W. (1993). Weakness in the transient visual system: A causal factor in dyslexia? *Annals of the New York Academy of Sciences*, *682*, 57-69.

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

Lovett, M. W., Barron, R. W., & Forbes, J. E. (1994). Computer speech-based training of literacy skills in neurologically impaired children: A controlled evaluation. *Brain and Language, 47*, 117-154.

Lyon, G. R. (1994). Critical issues in the measurement of learning disabilities. `In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities*, (pp. 279-333). Baltimore, MD: Paul H. Brookes.

Lyon, G. R. (2002). Reading development, reading difficulties, and reading instruction: Educational and public health issues. *Journal of School Psychology, 40,* 3-6.

Lyon, G. R., & Moats, L. C. (1997). Critical conceptual and methodological considerations in reading intervention research. *Journal of Learning Disabilities, 30*, 578-588.

Manis, F. R., Doi, L. M., & Bhadha, B. (2000). Naming Speed, phonological awareness, and orthographic knowledge in second grades. *Journal of Learning Disabilities, 33*, 325-333.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies in Reading, 3*, 129-157.

Martin, F., & Lovegrove, W. (1984). The effects of field size and luminance of on contrast sensitivity differences between specifically reading disabled and normal children. *Neuropsychologia, 22*, 73-77.

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

McPhillips, M., & Sheehy, N. (2004). Prevalence of persistent primary reflexes and motor problems in children with reading difficulties. *Dyslexia: An International Journal of Research and Practice, 10*, 316-338.

Meyer, M. S., & Felton, R. H. (1999). Repeated reading to enhance fluency. Old approaches and new directions. *Annals of Dyslexia, 49,* 283-306.

Meyler, A., & Breznitz, Z. (2005). Visual, auditory, and cross-modal processing of linguistic and nonlinguistic temporal patterns among adult dyslexic readers. *Dyslexia, 11*, 93-115.

Merzenich, M.M., Jenkins, W. M., Johnston, P., Schreiber, C., Miller, S. L., & Tallal, P. (1996). Temporal processing deficits of language learning impaired children ameliorated by training. *Science, 271*, 77-81.

Montgomery, C. R., Morris, R. D., Sevcik, R. A., & Clarkson, M. G. (2005). Auditory backward marking deficits in children with reading disabilities. *Brain and Language, 95,* 450-456.

Morris, R. D., Steubing, K. K., Fletcher, J. M., Shaywitz, S. E., Lyon, R., Shankweiler, D., Katz, L., Francis, D., & Shaywitz, B. A. (1998). Subtypes of reading disability: Coherent variability around a phonological core. *Journal of Educational Psychology, 90,* 347-373.

National Institute of Child Health and Human Development. (2000). Report of the National Reading Panel. Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction: Reports of the subgroups (NIH Publications No. 00-4754). Washington, DC: U.S. Government Printing Office

Nicolson, R. I., & Fawcett, A. J. (1994). Comparison of deficits in cognitive and motor skills among children with dyslexia. *Annals of Dyslexia, 44*, 147-164.

Nicolson, R. I., & Fawcett, A. J. (1999). Developmental dyslexia: The role of the cerebellum. *Dyslexia: An International Journal of Research and Practice*, 5, 155-177.

Nicolson, R. I., & Fawcett, A. J. (2001). Developmental dyslexia: The cerebellar deficit hypothesis. *Trends in Neuroscience, 24*, 508-511.

Pavlidis, G. T. (1981). Do eye movements hold the key to dyslexia? *Neuropsychologia*, *19*, 57-64.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L. C. Ehri, & R. Treiman (Eds.) *Reading Acquisition* pp. 145-174: Hillsdale, NJ: Lawrence Erlbaum Associates.

Pinker, S. (1994). The *language instinct*. New York: William Morrow Inc.

Portnoy, R. A., & Aronson, A. E. (1982). Diadochokinetic syllable rate and regularity in normal and in spastic and ataxic dysarthic subjects. *Journal of Speech and Hearing Disorders, 47*, 324-328.

Rack, J. P., Snowling, M., Hulme, C, & Gibbs, S. (2007). No evidence that an exercise-based treatment programme (DDAT) has specific benefits for children with reading difficulties. *Dyslexia: An International Journal of Research and Practice, 13,* 97-104.

Raudenbush, S.W., & Bryk, A.S. (2002). *Hierarchical Linear Models: Applications and data analysis methods* (2nd Edition). Thousand Oaks, CA: Sage.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.

Reynolds, D., & Nicolson, R. I. (2007). Follow-up of an exercise-based treatment for children with reading difficulties. *Dyslexia: An International Journal of Research and Practice, 13*, 78-96.

Reynolds, D., Nicolson, R. I., Hambly, H. (2003). Evaluation of an exercise-based treatment for children with reading difficulties. *Dyslexia: An International Journal of Research and Practice, 9*, 48-71.

Savage, R. (2004). Motor skills, automaticity and developmental dyslexia: A review of the research literature. *Reading and Writing, 17*, 301-324.

Savage, R., & Frederickson, N. (2005). Evidence of a highly specific relationship between rapid automatic naming of digits and text-reading speed. *Brain and Language*, *93,* 152-159.

Savage, R., Frederickson, N., & Goodwin, R. (2005). Evaluating current deficit theories of poor reading: Role of phonological processing, naming speed, balance automaticity, rapid verbal perception, and working memory. *Perceptual and Motor Skills, 101*, 345-361.

Shaw, S. F., Cullen, J. P., McGuire, J. M., & Brinckerhoff, L. C. (1995). Operationalizing a definition of learning disabilities. *Journal of Learning Disabilities, 28*, 586-597.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (Specific Reading Disability). *Biological Psychiatry, 57*, 1301-1309.

Silver, C., Pennett, D-L., Black, J., Fair, G., & Balise, R. (1999). Stability of arithmetic disability subtypes. *Journal of Learning Disabilities, 32*, 108-119.

Slattery, T., Pollatsek, A., & Rayner, K. (2006). The time course of phonological and orthographic processing of acronyms in reading: Evidence from eye movements. *Psychonomic Bulletin & Review, 13*, 412-417.

Stanovich, K. E., & Siegel, L. S. (1994). Phenotypic performance profile of children with reading disabilities. *Journal of Educational Psychology, 86*, 24-53.

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neuroscience, 20*, 145-151.

Sunseth, K., & Bowers, P. G. (2002). Rapid naming and phonemic awareness: Contributions to reading, spelling, and orthographic knowledge. *Scientific studies of reading, 6*, 401-429.

Swanson, H. L., Trainin, G., Necoechea, D. M., & Hammill, D. D. (2003). Rapid naming, phonological awareness, and reading: A meta-analysis of the correlation evidence. *Review of Educational Research, 73*.

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

Tallal, P. (2003). Language learning disabilities: Integrating research approaches. *Current Directions in Psychological Science, 12*, 206-211.

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

Tallal, P., Stark, R. E., & Mellits, E. D. (1985). Identification of language-impaired children on the basis of rapid perception and production skills. *Brain and Language, 25*, 314-322.

Tiffany, W. R. (1980). The effects of syllable structure on diadochokinetic and reading rates. *Journal of Speech and Hearing Research, 23*, 894-898.

Torgesen, J. K. (2005). Recent discoveries on remedial interventions for children with dyslexia. In M. Snowling, C. Hulme, & Malden, M. (Eds.), *The science of reading: A handbook.* Boston, MA: Blackwell Publishing.

Torgesen, J.K., & Wagner, R.K. (1996). *The Comprehensive Test of Reading Related Phonological Processes (CTRRPP).* Tallahassee, FL: Author.

Torgesen, J.K., Alexander, A. W., & Wagner, R. K. (2001). Intensive remedial instruction for children with severe reading disabilities: Immediate and long-term outcomes from two instructional approaches. *Journal of Learning Disabilities*, *34*, 33-58.

Torgesen, J. K., Wagner, R. K., Rashotte, C.A. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second- to fifth-grade children. *Scientific Studies of Reading, 1*, 161-185.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of word reading efficiency.* Austin, TX: Pro-Ed.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, *45*, 2-40.

Vellutino, F. R., Scanlon, D. M., & Lyon, G. R. (2000). Differentiating between difficult-to-remediate and readily remediated poor readers: More evidence against the IQ-achievement discrepancy definition of reading disability. *Journal of Learning Disabilities, 33*, 223-238.

Vellutino, F. R., Scanlon, D. M., & Tanzman, M. S. (1994). Components of reading ability: Issues and problems in operationalizing word identification, phonological coding, and orthographic coding. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities*, (pp. 279-333). Baltimore, MD: Paul H. Brookes.

Vitiello, B., Ricciuti, A. J., Stoff, D. M., & Behar, D. (1989). Reliability of subtle (soft) neurological signs in children. *Journal of the American Academy of Child and Adolescent Psychiatry*, 749-753.

Vukovic, R. K., & Siegel, L. S. (2006). The double-deficit hypothesis: A comprehensive analysis of the evidence. *Journal of Learning Disabilities, 39*, 25-47.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., Forbes, P., & Wypij, D. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. *Child Development, 72*, 37-49.

Waber, D. P., Wolff, P. H., Forbes, P. W., & Weiler, M. D. (2000). Rapid automatized naming in children referred for evaluation of heterogenous learning problems: How specific are naming speed deficits to reading disability? *Child Neuropsychology, 6*, 251-261.

Waber, D. P., Wolff, P. H., Forbes, P. W., & Weiler, M. D. (2004). Neurodevelopmental characteristics of children with learning impairments classified according to the double-deficit hypothesis. *Journal of Learning Disabilities, 37*, 451-461

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology, 30*, 73-87.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1997). Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: A 5-year longitudinal study. *Developmental Psychology, 33*, 468-479.

Wagner, R., Torgesen, J., & Rashotte, C. (1999). *Comprehensive Test of Phonological Processing*. Austin, TX: Pro-Ed Inc.

Wagner, R. K., Torgesen, J. K., Laughon, P., Simmons, K., & Rashotte, C. A. (1993). Development of young readers' phonological processing abilities. *Journal of Educational Psychology, 85*, 83-103.

Wilkinson, G. S. (1993). *Wide range achievement test (WRAT)*. Wilmington, DE: Wide Range, Inc.

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

Wolf, M., Bally, H., & Morris, R. D. (1986). Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired readers. *Child Development, 57*, 988-1000.

Wolf, M., & Bowers, P. G. (1999). The double deficit hypothesis for the developmental dyselxias. *Journal of Educational Psychology, 91*, 415-438.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33*, 387-407.

Wolf, M., & Katzir- Cohen, T. (2001). Reading fluency and its intervention. *Scientific Studies of Reading, 5*, 211-239.

Wolff, P. H. (1999). A candidate phenotype for familiar dyslexia. *European Child & Adolescent Psychiatry, 8*, 22-27.

Wolff, P. H. (2002). Timing precision and rhythm in developmental dyslexia. *Reading and Writing, 15*, 179-206.

Wolff, P. H., Cohen, C., & Drake, C. (1984). Impaired motor timing control in specific reading retardation. *Neuropsychologia, 22,* 587-600.

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

Wolff, P. H., Michel, G. F., & Ovrut, M. (1990b). Rate and timing precision of motor coordination in developmental dyslexia. Developmental Psychology, 26, 349-359.

Wolff, P. H., Kotwica, K., Obregon, M. (1998). The development of interlimb coordination during bimanual finger tapping. *International Journal of Neuroscience, 93,* 7-28.

Wolk, L., Edwards, M. L., & Conture, E. G. (1993). Coexistence of stuttering and disordered phonology in young children. *Journal of Speech and Hearing Research, 36,* 906-917.

Woodcock, R W. (1987). *Woodcock reading mastery test-revised.* Circle Pines, MN: American Guidance Service.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*, 3-29.