11-28-2007

Timing Variables in Reading and Language: The Relation of Naming Speed and Motor Speed to Auditory Temporal Processing

Cynthia M. Zettler
Georgia State University

TIMING VARIABLES IN READING AND LANGUAGE:

THE RELATION OF NAMING SPEED AND MOTOR SPEED TO AUDITORY TEMPORAL PROCESSING

by

CYNTHIA M. ZETTLER

Under the Direction of Dr. Marsha G. Clarkson and Dr. Rose A. Sevcik

ABSTRACT

Naming speed, motor skill, and auditory temporal processing (ATP) are constructs that are important to reading and language. These variables require processing timing information inherent in the stimulus or processing stimuli rapidly. ATP deficits are found in individuals with reading impairments, but studies are conflicting regarding the relationship between reading and ATP. This study examined relationships between naming speed, motor speed, and ATP, and centered on possible factors why inconsistencies have occurred across studies examining the association between reading and ATP. If the timing element of naming speed (rapid automatized naming-RAN) and of motor speed is common to ATP, then RAN and motor speed should predict thresholds for three auditory tasks (CMR, backward masking, and the precedence effect with TOJ) known to require temporal processing.

Tasks were administered to adult participants in order to examine the effects with skilled readers. Many of the variables were skewed and there were multiple outliers that altered the analyses. Ultimately, 75 participants were included in the final data set. Results indicated that

RAN did not predict thresholds for any of the masking tasks given. However, motor speed predicted thresholds for one CMR and two backward masking tasks, suggesting that motor speed should be controlled for in research assessing the contribution of ATP to reading or language. Neither naming speed nor motor speed predicted localization performance. Non-verbal intelligence predicted performance on several of the masking tasks, consistent with previous research. Performance on all three auditory tasks was similar to that reported in the literature assessing smaller samples of participants. Although the suggestion of a general timing component is not supported, the relationships found between motor speed and several auditory temporal measures indicate that the underlying timing elements are not independent.

INDEX WORDS: Reading, Language, Auditory temporal processing, Naming speed, Motor speed, Adults

TIMING VARIABLES IN READING AND LANGUAGE:

THE RELATION OF NAMING SPEED AND MOTOR SPEED TO AUDITORY TEMPORAL PROCESSING

by

CYNTHIA M. ZETTLER

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

In the College of Arts and Sciences

Georgia State University

2007

TIMING VARIABLES IN READING AND LANGUAGE:

THE RELATION OF NAMING SPEED AND MOTOR SPEED TO AUDITORY TEMPORAL PROCESSING

by

CYNTHIA M. ZETTLER

Committee Chairs: Marsha Clarkson
Rose A. Sevcik

Committee: Robin D. Morris
Colleen O'Rourke
Mary Ann Romski

Electronic Version Approved:

Office of Graduate Studies
College of Arts and Sciences
Georgia State University
December 2007

ACKNOWLEDGMENTS

Numerous people supported me and played an integral role in seeing me through graduate school. First, I want to extend my gratitude to my dissertation committee, several of whom I worked with throughout my entire graduate career. Marsha- Thank you for always seeing the best in me. Rose- Your enthusiasm and encouragement helped me to remain focused on the light at the end of the tunnel. Robin- Thank you for showing me what is possible when one puts his/her mind to a goal. MaryAnn- You helped to shape my thinking, providing a bridge between my interests that I will continue to explore for years to come. Colleen- I am grateful for the expertise you contributed to this project; I'm only sorry we didn't get to work together more.

My family was also a great motivator, pressing me to persevere. Dad- for all you have believed in me and sacrificed for me, I thank you. Mom- Although you knew my finishing this meant my leaving, you continued to provide me with your support. My Grandparents- Your faith in me has helped to build great confidence. Carrie- for having three adorable kids who remind me not to work *too* hard!

Others so close they might as well be family provided endless encouragement. "Momma and Papa Pea" Greeley- You have become an extra set of parents for me over the years, and have always been there for me. I am fortunate to have you in my life. Matt- You have put up with a lot of difficult times and stood by me through it all. It's finally time to celebrate.

Others helped to make this study logistically possible… Thank you to Michael Owren for allowing me to use the lab space, and also to the many student participants who gave their time and energy to this project.

…And for mentors who cannot be categorized. Elizabeth- You listened endlessly and motivated me to keep going, making it possible for me, too, to experience the "internal giggle."

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Literature Review

Reading is the "process of extracting and constructing meaning from written text for some purpose" (Vellutino, Fletcher, Snowling, & Scanlon, 2004, p. 5). At its core, reading involves the coordinated skill of the components underlying word identification, including phonology, orthography, and letter identification. A lack of proficiency in any one of these areas may significantly impair reading ability. A developmental reading disability (RD) is one of a number of disorders classified under the diagnostic category of learning disabilities (LD). A learning disability is an exclusionary classification that refers most commonly to a child who has difficulties in math, writing, spelling (encoding), reading (decoding), speaking and/or listening that cannot be accounted for by general cognitive ability or opportunity to learn and therefore is "unexpected" (Lyon, 1994, p.xv). Since the 1960's, an extensive body of research has been directed at determining the factors that contribute to the various forms of LD (Moats & Lyon, 1993). In particular, a considerable amount of research in the field of LD has concentrated on illuminating the factors influencing reading ability, reflecting the greater prevalence of specific reading disability relative to other learning disorders (Lyon, Fletcher, & Barnes, 2003).

Traditionally, the definitional criterion for RD was that of an IQ-discrepancy, whereby individuals with a discrepancy of more than one standard deviation (SD) from the mean between measures of real and/or non-word reading and measures of non-verbal intelligence have been classified as reading-disabled ("specific reading retardation," Rutter & Yule, 1975). However, more recent research has challenged this criterion for RD, suggesting that those readers who may not demonstrate a discrepancy but nonetheless are poor readers constitute a second classification of reading disability, one in which concomitant cognitive deficits may play a role in the development of reading and other learning problems that keep these so-called "garden-variety" or “low-achieving” poor readers lagging behind their chronological age mates (Lyon et al., 2003; Stanovich, 1988). In spite of the way reading is defined, however, impairments can be found in one or more key areas that may influence one’s reading ability to varying degrees. These areas and abilities include phonological awareness, rapid naming, motor speed, and auditory temporal processing.

Phonological Awareness

Although a number of variables share a relationship with reading ability, much of the research in the study of reading has attended to the influence of phonological awareness on decoding ability in single word reading. Indeed, a considerable amount of research has identified phonological processing impairment as playing a significant role in the development of RD (Adams, 1990). Phonological awareness is a broad term that refers to one’s ability to understand that sounds in written language correspond to sounds in spoken language (i.e., letter-sound relationships), and can be assessed using exercises such as rhyming and syllable manipulation. Phonological awareness includes phonemic awareness, the ability to decompose words in spoken language into their constituent sounds and manipulate those sounds to create new words, such as that required by a phoneme deletion exercise (e.g., “Say ‘sit.’ Now say ‘sit’ without saying ‘/s/’.”). As such, phonemic awareness represents a more specific level of phonological awareness. Research assessing the determinants of RD suggests that a lack of phonological awareness, and in particular, a lack of phonemic awareness, plays a principal role in RD, as the ability to understand and manipulate letter-sound relationships required for understanding the fine phonemic contrasts used in reading is central to reading ability (Adams, 1990; Liberman & Shankweiler, 1985; Stanovich, 1988; Wagner & Torgesen, 1987). Readers who have difficulty with such letter-sound relationships likely will have problems in the earliest decoding stages of reading, making reading slow and laborious. Consequently, it is often the evaluation of an individual's phonological awareness abilities that provides the diagnostic information necessary to make a classification of RD.

The impact of phonological processing on reading ability has been researched extensively. In a landmark study exploring the theme of phonological processing as a primary construct underlying reading ability, Wagner and Torgesen (1987) compiled the extant empirical reports on three components of phonological processing that were examined independently in their relation to reading: phonological awareness, phonological recoding in lexical access (the process of directing a written word to its sound-based, lexical referent as in rapid naming), and phonetic recoding to maintain information in working memory (the maintenance of the converted sound-based referents for rehearsal in the working memory system). Wagner and Torgesen (1987) found that the three components likely shared a similar ability, with each component tapping into phonological processing. Moreover, using longitudinal correlational studies as evidence, the authors concluded that phonological awareness ability independently played a causal role in the development of reading ability.

The influence of phonological processing impairments also has been studied as it relates to language. Individuals with difficulties in the language domain commonly show difficulties in reading and therefore are at an increased risk for the development of RD (Wolff, 2002). Catts (1995) reported on a longitudinal study with 100 children with expressive language impairments who presented with phonological, vocabulary, and morpho-syntax impairments at kindergarten age. The results showed that by the second grade, approximately 50% of the children evidenced reading achievement scores that were at least one standard deviation below the mean. With rates this high, researchers studying reading must take into account the language histories of individuals with RD, paying particularly close attention to early deficits in phonological processing.

Although phonological awareness deficits were identified as a strong contributor of RD, Morris et al. (1998) noted that the heterogeneity of deficits found in many persons with reading disabilities indicated that oftentimes phonological deficits were not the only problem in those with RD, likely contributing to many of the conflicting results often found in the literature. For instance, many children with RD had cognitive, language, and/or perceptual deficits that compounded the reading disability, resulting in the development of a unique profile from that of someone with a phonological deficit alone. To evaluate the relative contribution of each of these factors in the possible formation of subtypes of reading disabilities, Morris et al. (1998) performed a cluster analysis on cognitive and language data from 232 children with reading or reading and math disabilities. Using both low-achievement and regression-corrected discrepancy criteria, children were placed into groups based on their reading scores from the letter-word identification and word attack subtests or the Calculations subtest of the Woodcock-Johnson Psycho-Educational Test Battery (Woodcock & Johnson, 1977) and the full-scale IQ (80 or greater) on the Wechsler Intelligence Scale for Children-Revised (WISC-R, Wechsler, 1974). The classification variables used as factors for subtyping that were administered to the children included phonological awareness, verbal short-term memory, rapid naming, lexical/vocabulary, speech production, visual/spatial, visual attention, and non-verbal short-term memory tasks. From these factors, nine subtypes were identified that constituted over 90% of the sample, including two groups that were non-disabled, one global-deficit, one global language, and five reading-disabled subtypes, four of which were characterized by deficits in phonological processing with other non-phonological deficits present (verbal short-term memory and rate,

rate, verbal short-term memory and lexical, and verbal short-term memory and spatial). The final RD subtype included children who did not exhibit a deficit in phonological processing, but did exhibit a rate deficit. Those children evidenced deficits in rapid naming, in addition to having other impairments. The study demonstrated that most children with RD have a range of deficits that may or may not include deficits in phonological awareness.

Given that phonological deficits typically are discovered in childhood, would one expect to find them in adults, regardless of whether they received intervention? As adults arguably have had more experience with print than children, it is possible that adults with prior diagnoses of RD would improve their phonological skills with experience and not demonstrate evidence of any phonological processing impairment. Bruck (1992) investigated this question in a sample of 36 children with dyslexia (specific reading disability), 39 adults with dyslexia, and 63 child and college-level good readers (20 adults). Participants were administered three phonological or phonemic awareness measures including syllable and phoneme counting and phoneme deletion. All measures were untimed, and all measures utilized nonwords. Participants were required to repeat the nonword prior to performing the required task. Results indicated that the adults with prior histories of dyslexia did not achieve age-appropriate or reading-level appropriate phonemic awareness skills in spite of many adults in the sample having satisfactory word-recognition ability. However, these adults did perform similarly to typically-developing children on the broader phonological measures of syllable and onset-rime distinction. Additionally, the study showed that the adults with dyslexia did not evidence age- or reading-level improvements in phonemic awareness skill outside of the improvement in the onset-rime task. Typical child readers, however, improved their phonemic awareness with increases in reading skill, whereas their onset-rime abilities did not change, a function of that ability reportedly having been acquired by study age (6 years) in the child readers. These results suggest that although they may be able to read sufficiently by word recognition, adults with prior histories of reading problems may continue to show deficits in phonemic awareness throughout their lives.

In spite of the large body of research dedicated to the relationship of phonological processing to reading ability and in particular, reading disability, other associations to reading have been discovered that have in common the requirement of speed of processing, rate or timing. Such constructs include rapid automatized naming (RAN), motor speed, and auditory temporal processing. Although the precise relationship of some of these variables to reading ability and to one another remains unclear, numerous studies have found that these timing-related variables influence or relate to reading skill across samples of both children and adults (Breznitz, 2003; Tallal, 1980; Wolf & Bowers, 1999; Wolff, 2002).

Naming Speed

Although the repeated finding of phonological impairments in individuals with RD indicated a strong influence of phonological awareness deficits in the development of reading disabilities, the subgroup found by Morris et al. (1998) comprised of children with RD who did not have phonological impairments despite having reading problems suggested that a phonological deficit was not the only route to a reading impairment, as those children exhibited a rate impairment exclusive of any phonological deficit. Citing this and additional evidence, Wolf and Bowers (1999) posited that a second core deficit is implicated in RD. Their double deficit model of developmental RD suggests that phonological processing and naming speed/RAN each contribute independently to successful reading. Rapid naming concerns the ability to rapidly recall and accurately say the name of some stimulus, typically a letter, number, color, or object. The ability to rapidly name letters, in particular, is of utmost importance for reading, as letters and their corresponding sounds must be recalled rapidly and accurately for fluent reading to take place. Readers with difficulty in rapid naming tasks may have sufficient phonological processing skills necessary for decoding words, but they will not be fluent readers if their rapid letter recall ability is taxed (Wolf & Bowers, 1999). Consequently, reading and reading comprehension can suffer as a result of a naming speed impairment. In sum, according to the double-deficit hypothesis, individuals with RD can have selective deficits in phonological processing, rapid naming, or both, and it is those readers with both impairments who tend to be the most severely affected in their reading ability (Wolf & Bowers, 1999).

Rapid naming tasks are characterized by whether the task includes orthographic recall (letters and numbers) or pictorial recall (pictures and colors). Good readers engaged in a rapid naming task frequently will read more fluently (i.e., faster and more accurately) on those tasks involving orthographic naming ability than on pictorial tasks (Klein, 2002). Conversely, although they are less fluent than good readers across all four tasks, by the second grade, readers with disabilities tend to have the most difficulty with the orthographic naming tasks (Wolf, Bally, & Morris, 1986).

Recent research supports the independence of naming speed deficits as a second predictor of RD. Wolf et al. (2002) provided empirical support for the existence of a naming speed deficit in 144 second- and third-grade children with reading impairment using both IQ-discrepant and non-discrepant classifications of RD. Children performed a variety of measures tapping phonological and rapid naming components of reading skill, including the word identification, word attack, and passage comprehension subtests of the Woodcock Reading Mastery Test-Revised (Woodcock, 1987) and the letters subtest of the Rapid Automatized Naming Test (Denckla & Rudel, 1976), in addition to several other measures, including the Kaufman Brief

Intelligence Test (KBIT; Kaufman & Kaufman, 1990). Multiple regression analyses indicated that both the phonological and naming speed measures accounted for unique variance in the reading measures given, signifying their independence as individual predictors of reading performance.

Support for naming speed deficits in readers with disabilities is also found in the adult population. Cirino, Israelian, Morris, and Morris (2005) explored the double-deficit hypothesis in a sample of 146 college students referred for learning difficulties. Participants were given a battery of both timed and untimed decoding (real word and nonword) and comprehension measures, the vocabulary subtest of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 1997), and the elision and blending subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999), as well as the letter and number naming subtests of the CTOPP as a measure of rapid automatized naming. Participants also were given a visual search and attention task as a measure of general processing speed. Several hypotheses were evaluated to explore the double deficit hypothesis in adults, including the relative contributions of phonological awareness and naming speed to both decoding and comprehension under timed and untimed conditions. The findings of the study are indicative of the complex relationship between phonological awareness and naming speed and their relationship to reading. Results demonstrated that both phonological awareness and naming speed predicted real word and nonword reading, with phonological awareness also predicting both timed and untimed measures of comprehension. Additionally, phonological awareness predicted untimed word and nonword reading, with greater effect sizes than that of naming speed. Timed word reading was predicted by phonological awareness, again to a greater extent than that of naming speed, but both phonological awareness and naming speed similarly contributed to timed nonword reading.

Phonological awareness evidenced a stronger relationship to comprehension than naming speed, for both timed and untimed measures. Consistent with that of children, the group classified as having a double-deficit had the lowest scores on each of the reading measures, both timed and untimed. Finally, 69% of adults met criteria for RD based on timed measures of decoding whereas only 21% met criteria based on untimed measures, with a similar disparity for timed and untimed comprehension measures. The authors suggested that timed measures may be more sensitive to adults with reading difficulties than untimed measures; however, it also may be the case that the timed measures overestimate the numbers of adults with reading problems, as it is "unlikely that all of these individuals who read slowly have 'true' RD" (Cirino et al., 2005, p.41).

A second study assessed naming speed in an adult sample that consisted of 133 parents of 70 children who were referred to a university clinic for an investigation of familial dyslexia (Miller et al., 2006). About 30% of the child sample met clinical criteria for dyslexia, and in most cases, both parents of the children participated in the study. Seventy-six individual parents reported having had some difficulty learning to read. Participants were administered the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), the Gray Oral Reading Test (GORT-3; Weiderholt & Bryan, 1992), the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1998), and two phonemic measures (elision and blending) along with the letters and numbers rapid naming subtests from the CTOPP (Wagner et al., 1999). Structural equation modeling indicated that phonological and rapid naming measures individually predicted reading achievement (measured as word identification, word attack, and fluency). Post hoc analyses classifying adults according to Wolf and Bowers' (1999) double-deficit hypothesis indicated that those parents with deficits in both phonological awareness and rapid naming (i.e., double-deficits) showed the poorest scores on measures of reading achievement, supporting the use of the model and the presence and independence of both deficits in an adult sample.

Although naming speed reliably predicts reading performance in both children and adults, it may not exclusively predict reading. Waber, Wolff, Forbes, and Weiler (2000) used receiver operating characteristic (ROC) curves to determine whether a group of 188 children (aged 7-11) with heterogeneous learning problems showed deficits in naming speed as evidenced by individuals with diagnoses specific to RD. Children had a full-scale IQ of 80 or above as measured by the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991) and did not meet criteria for parent or teacher rating of hyperactivity. Additionally, none of the children had any neurological impairment, and all spoke English as their primary language. Children were assessed with the RAN test (Denckla & Rudel, 1976) for letters, numbers, colors, and objects, and were given both timed (Sight Word subtest of the Test of Word Reading Efficiency-TOWRE; Torgesen, Wagner, & Rashotte, 1999) and untimed (Basic Reading composite of the Wechsler Individual Achievement Test- WIAT; WIAT, 1994) measures of reading ability to capture both the rate and accuracy components of reading as they relate to RAN. Children were assessed for reading ability using both IQ regression-based discrepancy and low achievement criteria. ROC analysis measured the accuracy of RAN latencies predicting group membership when both timed and untimed measures of reading were used.

Results indicated that nearly 68 % of the children in the sample showed naming speed deficits. Similar to results found by Cirino et al. (2005), of those children demonstrating a naming speed deficit, 40.6 % were classified as RD using the untimed WIAT, whereas 67.9 % were classified as RD using the timed TOWRE, indicating a significant increase in RAN detecting RD in samples where timing deficits were present. Additionally, children who had naming speed deficits were more likely to be classified as RD relative to those without such deficits, regardless of whether the measure of reading used was timed or untimed. Interestingly, the study also indicated that a large number of children with learning impairments who did not meet either discrepancy or low-achievement criteria for a reading disability did meet criteria for a naming speed deficit (60% when untimed reading measures were used, 51% when timed measures were used), suggesting the complexity of naming speed deficits in their relationship to reading by showing that naming speed deficits may be present even when RD is not.

The ROC analyses indicated that RAN latencies reliably differentiated between children with learning impairments and 115 children in Wolf and Biddle's (1995) control group used in this study to provide normative data comparisons. However, ROC curves also indicated that RAN latencies distinguished children with learning impairments who were good readers from the control sample, leading the authors to suggest that reading ability alone is "not sufficient to account for differences in naming speed between children referred for learning difficulties and controls" (Waber et al., 2000, p. 255).

In a follow-up study, Waber, Forbes, Wolff, and Weiler (2004) explored the neurodevelopmental characteristics from the data set of the 188 children with learning impairments classified according to the double-deficit hypothesis described in Waber et al. (2000). A notable exception was that relatively few children (n = 3) met criteria for a phonological only deficit; therefore this group was not included in the analysis. Waber and colleagues (2004) gave a large battery of tests to the children, including written and oral language measures, visuospatial processing measures, and motor and processing speed measures that were subjected to factor analysis, leading to the formation of five groups with each group representing one of these factors. Other measures were given, including rapid auditory processing, but due to the lack of a factor loading above .5 were not included in the subsequent analyses. Group X factor means comparisons indicated that children in the double-deficit group were the most impaired across all of the factors, with the greatest deficit exhibited for written language ability. However, this group also was significantly lower than the others on visuospatial processing, a deficit that outweighed their performance on the oral language factor, leading the authors to state that "the difficulties experienced by these children are by no means limited to the language domain" (Waber et al., 2004, p.457).

Thus, questions remain as to the precise nature of the relationship of naming speed to reading. It is possible that a broad timing deficit or a general cognitive or perceptual deficit may help to explain the relationship of naming speed to reading, or that a deficit in naming speed simply exacerbates any phonological deficit present. As Waber and her colleagues (2000) suggest, although the naming speed task appears to be a simple one, there are likely multiple processes at work when one is engaged in the RAN task, including executive function, processing speed, attention, and visual perceptual processing. Each of these processes may influence not only reading ability, but learning ability in general.

Katz, Curtiss, and Tallal (1992) showed further support that RAN deficits are not limited to individuals with RD. Katz et al. (1992) tested a large group of children with and without language impairment on the RAN test (Denckla & Rudel, 1976) and on a modified version that the authors developed to assess manual skills (RAN manual). The RAN manual test required the children to perform pantomimes of the function of the objects presented rather than stating the name of the object in the picture. Sixty-seven children with language scores at least one year below their expected age on measures of expressive and receptive language and fifty-four age-matched typically developing children participated in the longitudinal study starting at age four, and were re-evaluated at ages six and eight. At ages six and eight, participants completed other reading and motor skill tasks, including measures assessing decoding and comprehension, and a diadochokinesis task in addition to the RAN task. By age six, the children with language impairments were found to have reading impairments. For all children, performance on both RAN tasks improved with age (that is, children were quicker at verbally naming and performing the pantomimes). However, both RAN tasks distinguished the groups from one another, with the children with language impairments performing more slowly across both RAN tasks relative to control children. A number of correlations were found between the RAN tasks and the additional measures given, including RAN verbal and diadochokinesis, and RAN manual and a finger opposition task (touching each finger to the thumb in sequential order with the same hand) in the children with language impairments. These findings underscore the similar processes of timing and motor skill subsumed by both RAN tasks, and show the utility of RAN as a predictor of language impairment. One caveat, however, is that because the children with language impairments were found to have severe reading impairment at follow-up testing, it cannot be determined whether these children had naming speed deficits that were strictly related to the language impairment, or whether the deficits were simply a symptom of the reading impairment that was subsequently found. Further assessment of the relationship between naming speed and language skill is necessary to clarify this finding.

Motor Speed and the Influence of Timing

Recent research suggests that some individuals with dyslexia have motor coordination deficits. Such motor-related timing deficits in persons with dyslexia have been reported in the literature using measures of unimanual fingertip tapping to a metronome, bimanual motor coordination, and syllable rhyming (Wolff, 2002). Wolff (2002) pursued the suggestion of a timing deficit in dyslexia by testing 12 adolescents with dyslexia and age and gender-matched normal readers in two motor anticipation tasks and one rhythm production task. In the first task, participants tapped on a plate to the stable rhythm of a metronome, using one or both index fingers simultaneously. A computer recorded the “tap duration” (how long the finger stayed in contact with the plate) and inter-tap intervals. Taps that occurred before the metronome signal were classified as “anticipation” responses, whereas taps that occurred after the metronome signal were classified as “tracking” responses. Analyses of anticipation time indicated that the anticipation response was 3-4 times longer for the participants with dyslexia than that of the control participants, indicating a noticeable delay in response time for the participants with dyslexia. However, whether or not the participants had a history of attention problems was not reported. Given that attention deficits commonly co-occur with RD, it may be the case that the participants with dyslexia had a higher rate of attention problems in this sample, resulting in an inability to effectively control their finger tapping responses (e.g., either being impulsive or inattentive). Thus, the delay in response time by the participants with dyslexia also may suggest that there are some individuals who simply were inattentive to the stimuli presented.

In a second task, the metronome changed rates, and participants were told to change their tapping with the metronome changes. When the metronome switched rates, a delay occurred for all participants (i.e., a switch from anticipation to tracking for several taps). However, normal readers switched back to the anticipation response after 2-3 tracking responses, whereas the participants with dyslexia returned to anticipation after 5-6 tracking responses. Thus, the normal readers showed a faster recovery time in returning to the anticipation response.

In a third task, Wolff (2002) gave participants a rhythmic sample of taps to replicate (dominant finger only). Those who could replicate the pattern were asked to tap the pattern 10 times when (a) there was no metronome signal, tapping only to the participant's preferred rate, (b) to the metronome signal at the participant's preferred rate, and (c) when the metronome rate was increased by 25%. Whether or not the metronome signal was present, the normal readers were able to preserve the appropriate inter-tap intervals relatively well, having a slight decrement in performance when the metronome was on relative to when the participants were able to tap at their preferred rates without it. However, the participants with dyslexia had significant difficulty performing the rhythmic task at all (three participants could not perform the task even with practice). Although performance deteriorated for all participants when the metronome rate increased by 25%, the performance of the participants with dyslexia was nearly "indecipherable" (Wolff, 2002, p.195) at the increased rate. In all three tasks, the performance differences between groups were significant.

A second experiment by Wolff (2002) attempted to determine whether a speech task analogous to one of the finger tapping tasks also would show differences between the dyslexic and control groups. Two, three, or four unit combinations of the consonant-vowel (CV) /pa/ (e.g., /pa PA/) were repeated 10 times and the three and four syllable strings were repeated five times. All participants performed the two syllable task correctly, but the participants with dyslexia had significant difficulty with the three and four syllable strings, making errors of stress or of syllable insertions or deletions. The author suggests the experiments might be tapping into a "common set of underlying deficits in temporal information processing" (Wolff, 2002, p.202). The evidence of timing problems in reading disorders suggests that timing may be an important construct that may help provide a link between the various deficits seen in the disorder, including that of motor timing and naming speed.

As with naming speed deficits, however, timing deficits may reflect an impairment that affects learning in general. Waber et al. (2000) assessed motor timing in a heterogeneous sample of 100 children between the ages of 7 and 12 referred for learning problems. All children had a full-scale IQ over 80 and no attentional or behavioral disorder or neurological impairment. A control group of 243 similar-aged, non-learning-impaired children also met these criteria. Additionally, all children were given the basic reading, spelling, and math calculation subtests from the Wechsler Individual Achievement Test (WIAT; Wechsler, 1992). Children performed 10 motor tasks, including a unimanual tapping pattern (child taps with a metronome and then without at a rate of 1.5 Hz, once with the right hand, once with the left), a symmetric alternation pattern (children tap in alternating rhythm with the right and then the left index fingers at 3 and 4 Hz), and an asymmetric alternation pattern (children tap with the metronome with one index finger and follow with second index finger of the opposite hand every other metronome beat at 2, 3 and 4 Hz with the leading hand alternating). The results indicated that those children who had been referred for learning problems displayed greater variability in the precision of their taps than control children, and that timing precision predicted reading skill for all timing tasks given. The differences found in timing precision continued to predict not only reading and spelling, but also persisted for math calculation, suggesting that individuals with learning problems not restricted to reading show deficits in motor timing tasks as well. These findings highlight the diffuse nature of timing deficits in their relationship to reading, and suggest that processes that might interlink motor timing and other timing-related constructs (e.g., naming speed) share a complex relationship with reading ability.

Reasoning that phonological, orthographic, and semantic systems are independent but linked, Breznitz (2003) suggested that a deficit in speed of processing in one or multiple areas may lead to deficient word reading rates, providing opportunities for impairments in attention, working memory, and phonological processing to become more evident. Breznitz (2003) used behavioral and electrophysiological methods to provide support for a timing deficit in 20 typical adult readers and 20 impaired adult male, native Hebrew-speaking readers. Readers with dyslexia were diagnosed in childhood and had at least three years of remediation at the time of the study. Participants received measures of reading comprehension, accuracy, and speed, as well as IQ. The experimental tasks included word-reading, orthographic, phonological, orthographic-phonological choice, and rhyme decision tasks that tapped both phonological and orthographic abilities. Event-related potentials (ERPs) were acquired from electroencephalogram (EEG) data and complemented the behavioral data obtained from the participants. Both behavioral and ERP data provided information about participants' performance on each task, including reaction time as well as response accuracy. Behavioral results indicated that the participants with dyslexia showed significantly longer latencies on oral and silent reading time, phonological, orthographic, rhyming, homophone, and homograph (orthographic-phonological choice) reaction time, as well as making significantly more errors on oral reading and rhyming accuracy than control participants. ERP data indicated further that participants with dyslexia displayed significantly longer latencies at P2, N2, and N4 for the phonological tasks, and at N1 and N4 for the homophone task (also a phonological task) than control participants. No differences in latency were found between groups for the orthographic or homograph tasks.

The author proposed that disparities between phonological and orthographic processing speed in those individuals with dyslexia may be responsible for poor integration of the sub-processes in reading, leading to a bottleneck effect of slowed reading rates and impaired word-reading effectiveness. Unfortunately, information about the naming speed abilities of the participants with dyslexia was not provided (although participants with dyslexia were given a timed comprehension test that revealed scores that were slower than those of age-matched typical readers). Based on the double-deficit hypothesis (Wolf & Bowers, 1999), those individuals with a double-deficit in both phonology and naming speed likely would display speed of processing impairments in both phonological and orthographic systems. As Breznitz (2003) did not assess this possibility, the question remains as to whether orthographic speed deficits would be found in the ERPs of those individuals with a double-deficit, and subsequently if those deficits in speed of processing would be commensurate with deficits found in the phonological system. A finding such as this would support the presence of a timing deficit that crossed multiple systems, at least within the domain of reading, and perhaps in language as well.

Katz et al.'s (1992) assessment of the relationship between verbal and motor naming speed underscores the need for more research looking at the relationship between timing and motor skill and their relationship to language. Hill (2001) reviewed the extant literature on motor coordination deficits in specific language impairment (SLI), a language disorder characterized by normal cognitive abilities in the presence of morphosyntactical, pragmatic, vocabulary, phonological, fluency, and/or retrieval deficits. Hill (2001) discovered that motor impairments in the disorder also were widespread, and suggested that researchers formulating definitions of SLI need to consider the impact of impaired motor skill on language development. The relationship between verbal communication and motor coordination is apparent when considering that speakers often use gestures when they talk, and the rhythmicity of hand movements tends to coincide with the grammar of a sentence spoken (Wolff, 2002).

Whereas in SLI motor coordination deficits complement the core disorder of grammatical and syntactic deficiency, in childhood apraxia of speech (CAOS) they are a defining feature.

CAOS is a developmental speech disorder in which a child is unable to form the fine motor movements necessary for intelligible speech, producing familiar words inconsistently and having problems producing speech sounds in isolation (McCormick, 2000). As with SLI, CAOS results in high comorbidity with RD, with deficits ranging from spelling problems (McCormick, 2000) to the identification and discrimination of degraded vowels (Maasen, Groenen, & Crul, 2003). Thus, multiple speech and language disorders have similar motor and timing deficits and appear to have a relationship with the possible development of RD.

The timely execution of skilled oral motor movements is necessary for fluent speech to occur. The relevance of perceptual and motor skills with regard to speech is well documented. Liberman, Cooper, Shankweiler, and Studdert-Kennedy (1967) proposed a now classic theory of speech perception known as the motor theory of speech. The central tenet of the theory is that perception and production are intimately linked. Because there is no one-to-one correspondence between what the speaker is saying and what the listener is hearing at the level of the phoneme, there must be a "speech decoder" to decipher the information. The authors propose that this decoder is the speech articulators of the speaker. A listener understands what a speaker is saying not by the breakdown of individual phonemes in the speech stream by the listener's auditory system, but rather by the perception of the movement of the speaker's articulators. According to this theory, it follows that because of the motoric basis between perception and production and the importance of timing, persons with language or reading impairments who have poor rapid naming and poor motor coordination skills also may show poor performance on measures assessing auditory perceptual timing tasks. A person who cannot produce the rapid, fluent, articulatory movements necessary for speech production may not be able to accurately perceive the rapid, fluent, articulatory movements of others necessary to form an accurate perception of what is being said.

Empirical support for a relationship between fluent articulation and fluent receptive language comes from studies of the KE family. The KE family possesses an inherited form of developmental speech and language deficit, leading to both expressive and receptive language difficulties (Alcock, Passingham, Watkins, & Vargha-Khadem 2000; Lai, Fisher, Hurst, Varga-Khadem, & Monaco, 2001; Watkins, Dronkers, & Vargha-Khadem, 2002). For example, Alcock et al. (2000) measured the perception and production abilities of 9 affected members of the KE family and 51 control participants using pitch, melody, and rhythm discrimination tasks and pitch, melody, and rhythm production tasks. Results indicated no differences between groups for either perception or production on the pitch and melody tasks. On the rhythm perception task, the affected family members discriminated significantly fewer rhythms than control participants. On the rhythm production task, however, affected family members produced significantly fewer rhythms than controls, both vocally and manually. The authors cautioned against the temptation to suggest that a generalized timing deficit exists, but concluded that members of the KE family have a timing deficit in vocal and manual motor control in conjunction with the speech and language deficit that may be the underlying result of both a sequencing deficit and a "fine-grained" timing deficit (Alcock et al., p.45). The evidence of timing problems in both language and reading disorders suggests that auditory temporal processing may help provide a link between the various deficits seen in the disorders.

Auditory Temporal Processing

Auditory temporal processing concerns the ability to use the timing information in a sound stimulus to identify or discriminate sounds (Moore, 1997). As Moore (1997) notes:

> Time is a very important dimension in hearing, since almost all sounds fluctuate over time. Furthermore, for sounds which convey information, such as speech and music, much of the information appears to be carried in the changes themselves, rather than in the parts of the sounds which are relatively stable (p.148).

The suggestion that a timing deficit in auditory perception could play an instrumental role in the development of RD became known as the auditory temporal processing deficit hypothesis and largely was built on the work of Tallal (1980). Tallal (1980) posited that an auditory perceptual timing deficit could lead to impaired speech perception, thereby influencing the development of a phonological processing deficit. Tallal (1980) tested twenty 8-12 year-old children with reading delay (performance on a standardized reading test at least one year below that expected based on age and grade) on a battery of auditory perceptual tests and compared them with that of twelve 8 ½ year-old typically-reading children. The participants completed the Auditory Repetition Test, a set of tests that Tallal gave to children with language impairments in 1976 that included assessments of temporal order judgments and perception of rapidly-presented stimuli at a range of interstimulus intervals (ISIs). The children with RD performed more poorly than the control participants on both the rapid perception and sequencing test as the ISI decreased, leading Tallal (1980) to conclude that the children with RD had a deficit in processing rapidly-presented auditory stimuli. An additional assessment of non-word reading demonstrated a correlation between the reading measure and performance on the auditory tasks. Tallal (1980) suggested that this correlation was support for children with RD having a deficit in auditory temporal processing.

Although others have failed to replicate this research using similar stimuli that manipulated ISI (Brier, Gray, Fletcher, Foorman & Klaas, 2002; McAnally, Castles, &

Bannister, 2004), significant results have been obtained with a diverse range of auditory stimuli, including a reduced sensitivity found in adult listeners with dyslexia for amplitude-modulated (AM) noise, both behaviorally and physiologically (Menell, McAnally, & Stein, 1999), deficits in backward masking in adolescents with dyslexia (Rosen & Manganari, 2001), and deficits in the detection of frequency differences, of a tone in narrowband noise, and of AM (Amitay, Ahissar, & Nelken, 2002), and impaired judgments of temporal order (Montgomery, unpublished dissertation, 2002) in individuals with RD.

In spite of these findings, however, research examining the influence of auditory temporal processing on the development of RD often has been plagued by inconsistent results, with some studies reporting that individuals with dyslexia perform more poorly than control participants (e.g., Tallal, 1980), others reporting no differences (Nittrouer, 1999), and still others with mixed findings (Rosen & Manganari, 2001). For example, in addition to the differences reported previously between adults with and without dyslexia, Amitay et al. (2002) also assessed comodulation masking release (CMR). CMR is an auditory task in which a listener's ability to detect a pure-tone signal in a single amplitude-modulated (AM) noise masker is compared to his/her ability to detect that same signal in multiple amplitude-modulated noise maskers with the AM of the maskers being modulated at the same rate and phase (i.e., "coherent AM," Hall & Grose, 1990). The listener's requirement is to combine the temporal information from the fluctuation of the maskers across differing frequency regions to facilitate signal detection. Since individuals with dyslexia showed decreased responsiveness to AM stimuli (Amitay et al., 2002; Menell, et al., 1999), and perception of coherent AM is integral to the CMR task (Hall, Haggard, & Fernandez, 1984), CMR should be reduced in listeners with dyslexia relative to normal readers. Nonetheless, Amitay et al. (2002) found no differences between groups when measuring

CMR monaurally with a two-alternative, forced choice (2AFC) procedure in which participants indicated which of two sounds contained a 1000-Hz tone.

What could account for this apparent inconsistency? First, participants in the Amitay et al. (2002) study were all native Hebrew speakers, a language that consists of both shallow and deep orthography. Given that English is a deep orthography, the orthographic difference between Hebrew and English may be an important one. In alphabetic languages, a deep orthography is one in which letters in the written language can represent more than one sound in spoken language, and is a component of the English language that may be responsible for why native English speakers tend to have a higher incidence of phonologically-based impairments relative to those languages with more shallow orthographies such as German or Italian (Vellutino et al., 2004). Second, the participants in the Amitay et al. (2002) study were not classified according to whether or not they had naming speed deficits. Although naming speed deficits are more common than phonological deficits in poor readers who speak languages with shallow orthographies (Vellutino et al., 2004), because naming speed was not assessed, it cannot be determined how many participants met criteria for either naming speed or a double deficit. Consequently, it remains possible that naming speed has a more direct relationship with performance on the CMR task.

More generally, there may be additional reasons for the disparities across studies measuring basic auditory processing in individuals with reading impairments. For one, disagreements about what constitutes “auditory temporal processing” led some to differentiate between “rate of perception” and “perception of rate” in response to Tallal (1980), arguing that the latter was the more accurate definition (Studdert-Kennedy & Mody, 1995). Second, differences in the way RD/dyslexia is defined has led to difficulties in generalizing results across studies. For instance, studies that include only IQ-discrepant poor readers relative to those that include both discrepant and non-discrepant (low-achieving) readers may show different results based on this classification difference, as it is known that discrepant poor readers are more likely than non-discrepant poor readers to evidence deficits in naming speed (Wolf & Bowers, 1999). Classification may impact how the groups respond to other variables related to reading, such as auditory processing. Little research specifically has addressed this issue as it pertains to auditory processing in individuals with reading problems; however, Zettler, Sevcik, Morris, and Clarkson (in press) demonstrated that the thresholds for two complex masking tasks measuring auditory processing in children did not significantly differ based on IQ-discrepancy or low-achievement classifications of RD. Nevertheless, when attempting to delineate factors influencing RD, it is important to continue to be mindful of these potential sampling differences in such heterogeneous populations.

In addition to the growing body of literature on auditory temporal processing in persons with reading disabilities, auditory temporal processing has been explored in individuals with SLI and other language impairments with results suggesting that those with language impairments show deficits relative to control participants in a wide variety of tasks, including rapidly-presented auditory stimuli (Tallal & Piercy, 1973), masked thresholds (Wright et al., 1997), and tracking a fused auditory image (Visto, Cranford, & Scudder, 1996). Although previous research suggests that some people with language impairments have difficulty with auditory temporal processing, much remains to be understood about the limits of that impairment and how a perceptual deficit might influence or relate to the development of RD.

Because different auditory tasks may measure processing at various locations in the auditory system (possibly reflecting a breakdown in one region relative to another when processing impairments are found), a range of auditory tasks, including both monaural and binaural presentations of the sounds, are needed to assess how listeners use auditory temporal information to detect sounds in the environment. In addition to CMR, two additional psychoacoustic tasks that may provide useful information about how listeners process the timing information in sounds include backward masking, and judgments of temporal order in auditory space.

Comodulation masking release (CMR). Exclusive of Amitay et al. (2002), little research has focused on the influence of reading on CMR. Because CMR provides two separate thresholds for a listener's ability to identify a signal in amplitude-modulated noise in addition to the overall masking release, it provides a good measure of one's auditory processing efficiency. Although a listener's masking release (CMR) may be large, his/her thresholds also may be high, indicating poor processing efficiency. This pattern is common for comparisons of children's and adult's CMR, where children may show CMR consistent with that of adults in spite of having thresholds in the individual conditions that are as much as 5-7 dB higher than those of adults (Veloso, Hall, & Grose, 1990). Given that questions remain as to the relationship of RAN and motor speed to reading ability due to the possibility that general processing efficiency is diminished in individuals with reading problems, utilizing CMR as a measure of auditory processing efficiency may be especially fruitful in understanding the relationships between processing efficiency required for RAN and motor speed tasks and processing efficiency required for the CMR task.

One study attempting to determine whether children with RD demonstrated deficits in auditory temporal processing (Zettler et al., in press) measured detection thresholds in eighty-two 7-11 year-old children (31 with RD) for a 1000-Hz pure tone signal presented binaurally through headphones. Participants were classified as having a reading disability based on their performance on the Word Identification and Word Attack subtests of the Woodcock-Johnson III (Woodcock, McGrew & Mather, 2001) according to both IQ-discrepant and non-discrepant, low achievement definitions. Two conditions provided a measure of CMR. In the reference condition, the signal was centered in a 20-Hz wide noise band amplitude modulated at a rate of 10 Hz. The modulated masker condition included the reference condition plus eight co-amplitude modulated, 20-Hz wide flanking bands of noise, four on either side of the reference stimuli, with their center frequencies separated by 100 Hz. CMR was measured as the difference in thresholds between the modulated masker condition and the reference condition. Although children with RD demonstrated less CMR than controls (3.18 and 4.70 dB, respectively), the difference was not statistically significant. Several explanations could account for this nonsignificant finding, including the stimulus parameters used, the low rate of AM used, the possible low statistical power in the clinical group, or high variability in the overall sample. This sample variability may be an important reason for the lack of a significant finding, as Zettler et al. (in press) also did not assess naming speed in the participants. It remains possible that naming speed would have better differentiated the groups than did the phonological measures used.

Backward masking. In the natural environment, sounds that a listener attends to (“signals”) must be perceptually separated from the remaining auditory stimuli (“noise”) to help to make sense of what is being heard. Backward masking is a monaural task that demonstrates how well the auditory system is able to separate noises that follow signals of similar frequency closely in time. In the backward masking task, participants listen for a pure-tone signal that occurs prior to a broadband (or “bandpass”) noise masker, a noise masker that encompasses all frequencies. The task assesses temporal processing based on the duration between the signal and the masker. At short signal-masker durations, more masking occurs and the signal is obscured, whereas at longer durations less masking occurs, and the signal is more easily identified. Individuals with difficulty in the backward masking task require a greater signal level to detect the presence of the signal than those without such difficulty.

Backward masking also may assess spectral (frequency) processing ability. By removing a portion of the masker (i.e., creating a "spectral notch"), listeners must use the masker information in neighboring frequency regions to aid in signal detection. Because a portion of the noise is being removed, signal detection typically is easier in the notched-noise condition rather than in the bandpass condition. Backward masking has been explored frequently as a non-speech task that, in some studies, shows deficits in individuals with language-based impairments (Wright et al., 1997).

Research indicates that reading skill relates to backward masking thresholds (Griffiths, Hill, Bailey, & Snowling, 2003; Montgomery et al., 2005; Rosen & Manganari, 2001). Montgomery et al. (2005) tested fifty-two 7-10 year-old children on backward masking and backward masking, notched-noise conditions. One half of the children had a reading disability, classified according to both IQ-discrepancy and low-achievement criteria, and one half of the children were control participants without RD. Through headphones, participants listened for a 1000-Hz pure tone signal presented 20 ms prior to the onset of a 200-ms, broadband noise masker, with and without a spectral notch. After controlling for age and NV IQ, hierarchical regression analyses indicated that reading status predicted both backward masking and backward masking, notched-noise thresholds, supporting suggestions that children with RD have deficits in both temporal and spectral processing of sounds.

As with other auditory tasks in samples of individuals with reading impairments, however, results are conflicting, indicating a complex relationship between reading ability and backward masking. Rosen and Manganari (2001) assessed eight 11-14 year-old children with dyslexia (based on IQ-discrepancy criteria) and eight age-matched control participants on both speech and non-speech backward and forward masking tasks. A standard backward masking task was given in which the listener detected a 1000-Hz pure tone signal presented prior to the onset of a broadband noise masker or a notched-noise masker. Speech stimuli included the syllables "/ba/" and "/da/" and "/ab/" and "/ad/." If backward masking deficits impact speech perception, individuals with a backward masking problem would be expected to have difficulty with one set of stimuli ("/ba/" and "/da/") relative to the other ("/ab/" and "/ad/"). Because consonants contain brief bursts of energy relative to vowels, the vowel could have a masking effect on the perception of the preceding consonant, thereby creating the masking effect and resulting in impaired perception specific to those stimuli. However, in the "/ab/" and "/ad/" stimuli, forward masking, shown not to be problematic in individuals with RD, would play a greater role, and discrimination of these sounds should not be impacted. However, Rosen and Manganari (2001) did not find this result. Instead, participants with dyslexia performed more poorly relative to the control listeners in the standard (non-speech) backward masking configuration, but did not show disparities in discriminating the speech sounds. All of the adolescents with RD performed more poorly on their discrimination of the speech sounds. However, they performed more poorly than controls on their discrimination of all of the sounds, not just the ones hypothesized to be impacted by a backward masking deficit. The authors concluded that a linguistic or phonological-based deficit must be present to account for the findings unless the acoustic role is more complex than previously believed. Nevertheless, given the small number of participants in this study, the inclusion of only those individuals who met IQ-discrepancy criteria for dyslexia, and the lack of developmental data on typical adolescents' performance on complex masking tasks at the ages of the participants in Rosen and Manganari (2001), a larger sample size and the inclusion of individuals with low-achievement classifications of RD might have created a more complete picture of the speech and non-speech discrimination abilities of the adolescent population.

Backward masking also has been measured in adult listeners. In a modified test of tone-in-noise masking, Griffiths et al. (2003) assessed a group of 20 university students with dyslexia and 20 control students matched for age and IQ on a measure of auditory backward recognition masking (ABRM). ABRM stimuli consisted of four pairs of tones, three of which contained two 1000-Hz tones. The final tone pair, presented in either the third or fourth position, contained a tone in the pair that was higher than 1000 Hz, presented prior to the standard 1000-Hz tone, thus providing a measure of backward masking. The participants' task was to identify the tone pair that contained the tone higher than 1000 Hz at varying ISIs of either 200 or 20 ms. Results showed a subset of participants with dyslexia that performed poorly on the measure relative to the others. However, a subgroup of participants without phonological impairments also presented backward masking deficits. Interestingly, this result also was found by Rosen and Manganari (2001) for one control participant who was omitted from the study for lack of matching. It is unclear whether these individuals had reading impairments that were undetected by the phonological tests or whether they truly were unimpaired control participants. It remains a possibility that these individuals had deficits in naming speed that were undetected that may have explained their performance on the auditory backward masking tasks. Nevertheless, it appears that the deficits found in backward masking are highly variable across individuals, and may be explained by a number of factors potentially including, but not limited to, phonological processing.

Backward masking is a task that also has been explored in language disorders. Backward masking performance is significantly poorer for children with SLI than typically developing control children (Wright et al., 1997). Wright et al. (1997) tested sixteen 8-year-old children on backward masking and backward masking notched-noise conditions. Eight children were diagnosed with SLI and eight typically developing control children were matched for age and NV IQ. Results indicated that the children with SLI had significantly higher thresholds than the age-matched control children in both masking conditions, indicating that children with SLI evidenced problems with both temporal and spectral auditory processing ability.

Findings such as those mentioned above have led some researchers to seek a physiological basis for the results. McArthur and Bishop (2004) tested 32 adolescents (mean age ~14 years) on an auditory backward recognition masking task and a frequency discrimination (FD) task. Sixteen participants were classified as having SLI and 16 control participants were included after being matched for age and non-verbal IQ. An initial goal of the study was to determine what factors contribute to children with SLI showing poor auditory processing. A second goal was to determine whether rapid auditory processing or frequency discrimination ability was the primary auditory deficit seen in SLI. Four ABRM tasks required participants to identify a 600-Hz pure tone signal followed by a 1000-Hz noise masker for 20, 50, 150, or 300 ms at varying ISIs. In the FD task, the same 600-Hz, pure-tone stimulus was used as in the ABRM task, and a tone of a higher frequency (</= 800 Hz) was presented as a deviant tone that varied from trial to trial in a two-interval, forced-choice procedure. Participants identified the higher tone. Results for the ABRM task indicated that thresholds increased with decreasing ISI

for both groups. However, in the FD task the participants with SLI showed thresholds that were significantly higher than control participants. This finding appeared to be the influence of a subset of five of the youngest participants with SLI who also showed relatively poor nonword reading scores (given prior to auditory testing). The authors concluded that the performance of the participants with SLI appeared to be more suggestive of an inability to discriminate between two frequencies rather than an inability to perceive rapidly-presented stimuli.

To exclude possible behavioral influences such as attention or motivation, McArthur and Bishop (2004) conducted a second experiment to assess auditory event-related potentials (ERPs) in the same participants described previously. Stimuli presented were the same as for the FD task, with the 600-Hz tone presented as the standard stimulus and the 700-Hz stimulus presented as the deviant stimulus. Results showed that all of the participants with SLI showed decreased responsiveness in the N1-P2-N2 range relative to control participants, regardless of how they performed on the auditory tasks. That is, even listeners whose performance was consistent with the age-matched controls on the FD task still showed abnormal N1-P2-N2 auditory ERPs. This finding led the authors to speculate that all of the children with SLI had impaired auditory perceptual processing in their sample, but that the measures used for the FD task may not have been sensitive enough to detect those differences. In addition, the authors suggested that the auditory cortex, slow to mature in typically developing individuals, might be undergoing an even more protracted course of development in the participants with SLI (McArthur & Bishop, 2004).

Auditory masking also has been explored in children with Central Auditory Processing Disorder (CAPD). CAPD is a language disorder marked, in part, by disruptions in binaural auditory temporal processing with no peripheral hearing impairments, including an inability to understand speech in noisy conditions or to process sounds in reverberant environments (Keith, 1999). Wright and Reid (2002) measured masked thresholds in a group of thirteen 8-year-old and eight 12-year-old children with SLI or CAPD. Control participants included groups of 6-, 8-, and 10-year-old typically-developing children. Backward masking, simultaneous delay, and forward masking conditions were administered to the children using a 1000-Hz pure tone signal. Results indicated that the performance of the 12-year-old impaired group paralleled that of the 8-year-old control group, such that the thresholds of the impaired group were similar to that of the language age-matched control participants who were four years younger. Thus, the suggestion that the development of the auditory cortex may be delayed is supported in this sample of individuals with SLI and CAPD.

In sum, as with naming speed and timing, auditory backward masking shares a complex relationship with reading and language ability. It remains to be explained whether auditory deficits found in some persons with RD are a contributing factor to reading ability, or whether they are simply a characteristic of individuals in general, just as some people are better than others at sports or music. To answer this question, more research needs to be done, with careful focus on the characteristics and abilities of the participants, including their histories of speech and language development, experiences that could affect hearing, and familial histories of reading problems. Assessing adult participants with a range of reading abilities on multiple auditory masking tasks and focusing on the sample characteristics may help to answer this lingering question by providing a more complete picture of the attributes of the sample than has been provided in previous research, allowing for potential patterns in performance across tasks to be revealed.

Localization. The precedence effect is a localization phenomenon that allows sound sources to be localized in reverberant environments by suppressing those echoes occurring closely in time to the original sound source. In a laboratory environment, the classic stereo effect is created by placing two loudspeakers equidistant on either side of the listener and playing two sounds simultaneously. In this case, the sound is perceived as being directly in front of the listener. For increasing delays of 7-10 ms between the onset of one sound relative to the other, the sound appears to move toward the leading sound, resulting in the perception of a "phantom speaker." When one sound leads the other by 2-20 ms, the sound source is localized at the leading speaker. Beyond about 20 ms, the effect breaks down and listeners report hearing two sounds, although the identification of the location of the leading sound remains difficult (Litovsky, Colburn, Yost, & Guzman, 1999). At delays beyond 50 ms, listeners can discriminate the source of both sounds, and temporal order judgments (TOJ) are possible.

Montgomery (unpublished dissertation, 2002) tested 34 children (aged 7-9 years) diagnosed with RD and 24 control participants (aged 7-8 years) on their perception of the precedence effect (PE) at short delays and TOJ at longer delays. Two loudspeakers were placed 90^{o} from the participants' midline. Fourteen-ms clicks were played by one of the two loudspeakers in a single-source condition and from both loudspeakers with one speaker delayed relative to the other by 5, 10, 20, 50, 100, 200, and 400 ms in dual-source conditions. On single-source trials (implemented as a control condition), participants indicated which one of the two loudspeakers emitted the sound; on dual-source trials, participants indicated which loudspeaker emitted the sound first. Although results indicated no significant differences between children with RD and typically-developing children at very short delays (i.e., the PE), the group with RD performed significantly worse than control participants at the 400 ms delay, suggesting a deficit in making judgments of temporal order. Interestingly, four children had thresholds greater than the maximum 400 ms delay, resulting in no measurable thresholds for those participants.

Using a precedence effect paradigm, Visto et al. (1996) tested the ability of children with SLI to track a moving fused auditory image (FAI). Three groups of ten children were tested: 12-16 year-old children diagnosed with SLI, chronological age-matched children, and 6-12 year-old language age-matched children. All children had hearing within normal audiometric limits. A stationary FAI test analogous to the PE was first given as a control condition, with delays of .2, .3, .5, .7, 1.0, 4.0, or 6 ms. Click pairs were presented at a rate of 3/sec. Participants were told to indicate the speaker from which the sound originated. In the moving FAI test, participants were given a laser pointer to indicate the perceived location of the sound. One speaker played the first sound, and the second speaker played the second sound which was delayed by 0-.8 ms, ranging in .1 ms increments across a 90˚ arc. Thus, FAI locations ranged in 6 degree increments from 45˚ left to 45˚ right. No significant differences between groups occurred on the stationary task across groups, consistent with the PE findings of Montgomery (unpublished dissertation, 2002) reported earlier. However, for the moving FAI task, children with SLI performed similarly to the language age-matched group, and both the SLI group and the language age-matched group showed poorer tracking ability than the chronological age-matched group. The authors suggested that children with SLI were impaired in binaural temporal processing as measured by the precedence effect, performing similarly to children approximately four years younger than themselves. This apparent delay agrees with results found by McArthur and Bishop (2004), Visto et al. (1996), and Wright and Reid (2002), suggesting a possible delayed maturation of the auditory cortex in children with language and reading impairments over a range of tasks. Measuring auditory abilities in typical adult listeners should allow conclusions to be made regarding the relationship of auditory processing to language ability without this inherent confound of cortical development.

As presented in this review, the relationships among the variables that influence reading are complex. Indicative of this complexity, the literature reports numerous studies, some of them conflicting in their results, concerning the nature of the different dimensions of reading and auditory temporal processing (Mody, Studdert-Kennedy & Brady, 1997; Montgomery, Morris, Sevcik & Clarkson, 2005; Rosen & Manganari, 1999; Tallal, 1980), reading and visual processing (Eden et al., 1996), reading and visual speed of processing (Stein & Talcott, 1999), reading and phonological and orthographic processing speed (Breznitz, 2003), and motor speed (Waber et al., 2000). This complexity has extended to the study of reading and language, as additional studies explored the relationships between language and reading (Catts, 1995; Catts, Adlof, Hogan, & Weismer, 2005), and between language and phonological processing (Cooper, Roth, Speece, & Schatschneider, 2002). Phonological awareness research also has not been exempt from yielding disparate results across studies. In the literature on the contribution of phonological awareness to reading alone, differences emerged across studies that measured word decoding versus those that measured comprehension outcomes until Stanovich (1988) brought to attention that individuals with comprehension deficits represented a group with deficits unique from individuals with decoding deficits, and in so doing, intensified the research on subgroups of reading disabilities.

To begin to untangle these inherent complexities, it is necessary first to understand how these processes operate in typical readers. Moreover, although the majority of the research on reading comes from studies of children with reading impairments, it may be easiest to begin to understand the linkages between these constructs independent of the concomitant development of perceptual, motor, and cognitive systems. Studying the relationships among the various contributors to reading in unimpaired adult populations is important to understand how these processes interact in clinical populations of both children and adults. The present study attempted to clarify the relationships between variables that have been found to influence reading ability that contain an underlying timing component. The intent was not to suggest that an underlying timing deficit was responsible for RD, but rather to help to untangle some of the inconsistencies found in the literature to date. In particular, the focus was on providing future research with a foundation to better explicate the contribution of an auditory temporal processing deficit to the development of RD.

Because inconsistent results have been found across studies, a different approach to disentangling the relationship between temporal processing and language and reading disorders may be advantageous. Understanding the relationships between naming speed, timing, and measures of auditory temporal processing would provide an important explanation for disparities across studies if significant associations are found. Although it seems logical to link phonological processing with auditory processing to the extent that both deal with the perception of sounds, research has been inconclusive in determining the relationship between the two constructs. Given that auditory temporal processing has been the area of auditory perception most heavily researched in reference to reading disabilities, perhaps it would be more fruitful to explore the timing aspect of sound as it relates to naming speed and other timing variables to help uncover the contribution of temporal processing to reading. Moreover, research demonstrating that children with RD perform more poorly on measures of phonological processing than do those with language disorders such as SLI, together with the finding that children with SLI perform more poorly on measures of auditory temporal processing than do those with RD (Robertson, Joanisse, Desroches, Ng, & Terry, 2005) suggests that the connection between auditory temporal perception and RD may not be via the phonological processing deficit. Thus, identifying similarities or differences in perceptual deficits across language and reading disorders and studying how those abilities relate to the constructs believed to influence these disorders will contribute to the further understanding of the relationship between them and may inform assessment and diagnosis.

Extensive research has focused on a potential relationship between phonological processing and auditory temporal processing (Booth, Perfetti, MacWhinney, & Hunt, 2000; Farmer & Klein, 1995; Menell, McAnally, & Stein, 1999; Nittrouer, 1999; Rosen & Manganari, 2001; Studdert-Kennedy & Mody, 1995; Tallal, 1980), but no research has looked at how naming speed might relate to auditory tasks that are largely dependent on timing ability to identify sounds. If both phonological processing and rapid naming independently contribute to and influence the development of language and reading disabilities, then it is essential, when seeking out other relevant predictor variables, that these core influences be examined individually. If rapid naming is more closely linked to auditory temporal processing than is phonological processing, then studies with samples of people who have poor rapid naming skills also should show poor temporal processing. However, studies with samples of people who have only poor phonological processing skills would not show poor temporal processing, thus explaining some of the variability in findings across studies.

Hypotheses. Given that timing is an important construct in reading, it is necessary to examine the variables concerning aspects of timing in their relation to reading more precisely. Consequently, the present study examined whether phonological processing and rapid naming independently predicted performance on three auditory perceptual tasks in a large sample of typical adults. If naming speed predicts auditory thresholds independent of phonological processing, the results would provide an account for why studies in the extant literature have been inconsistent in determining the influence of an auditory perceptual deficit in RD. 1) If the timing component of naming speed is related to the timing component in auditory temporal processing, it was expected that naming speed would predict auditory thresholds over and above the influence of phonological processing. Given that phonological processing has been shown to correlate with auditory temporal processing, it was important to control statistically for phonological processing ability. IQ was controlled for in the equation as it correlates frequently with auditory processing measures.

An assessment of motor speed permitted the exploration of whether timing underlying the motor domain extended to the auditory domain as measured by tasks known to access temporal processing. 2) It was expected if the timing component in a general motor speed task was related to the timing component in auditory temporal processing that motor speed would predict auditory thresholds. Studying the relationships among the measures that contain a timing component previously shown to influence RD may allow researchers to better understand how timing deficits operate in RD. The results of this research may contribute to the assessment and measurement of auditory processing that subsequently can be applied to clinical populations of adults and children with reading and language deficits.

Chapter 2: Method

Participants

Seventy-five adult native English speakers (mean age 21.23 years, 53 females) were recruited to participate from the undergraduate psychology population at a large, urban university. A power analysis revealed that with power set to .90 and for a moderate effect size (.07) for each of three predictors (NVIQ, phonological processing, naming speed/ NVIQ, laterality index, average motor speed), a minimum of 58 participants provided a 9 in 10 chance of finding a significant effect. Five additional students participated in the study but were not included in the analyses; three were non-native English speakers, one student was taking antibiotic medication, and one student had only 75% of her hearing in her left ear. Additional descriptive summaries are reported in Table 1.

Participants performed a variety of measures to assess various motor speed, reading, language, and auditory processing abilities. The motor speed task consisted of participants performing a finger-tapping task in which they were required to tap as many times as they could in a specified period of time. The measure provided a general measure of motor speed using the index finger of each hand, and both dominant and non-dominant hand finger taps were recorded.

Participants were evaluated for phonological awareness (PA) ability with the elision and blending subtests, and were evaluated for naming speed with the letters, numbers, colors, and objects rapid naming subtests of the CTOPP (Wagner et al., 1999). A number of participants demonstrated difficulties in phonological processing or rapid naming on these tasks. Although the present study was concerned with the performance of unimpaired adults, the presence of phonological and naming speed problems in the sample reflect a normal distribution of

Table 1

Demographic and Descriptive Information of the Sample

Measure	Mean	SD	Range
Kaufman Brief Intelligence Test- Matrices	104.32	7.67	83-129
Laterality Index (ratio)	.05	.058	-.1569-.1719
Average Finger Taps, both hands	48.73	7.10	22.10-61.40
CTOPP Elision	92.67	15.05	60-110
CTOPP Blending	106.87	13.38	50-120
Phonological Composite (Elision and Blending)	99.49	15.49	50-120
RAN Composite (Letters and Numbers)	105.00	10.54	85-130
RAN Composite (Colors and Objects)	101.64	12.97	79-133
WRMT-Word Identification	98.55	8.65	81-136
WRMT-Word Attack	97.56	8.84	77-124
WRMT-Passage Comprehension	105.03	8.36	84-128
WRMT- Basic Skills (Word ID, Word Attack)	98.03	7.76	82-122
WRMT-Short Scale (Word ID, Passage Comp)	101.71	8.42	81-128
CELF-4 Core Language	126.28	8.05	98-142
CELF-4 Recalling Sentences	100.20	10.15	75-115
CELF-4 Formulated Sentences	107.00	8.74	75-120
CELF-4 Word Classes-Receptive	109.73	5.98	90-115
CELF-4 Word Classes-Expressive	108.67	7.68	85-125
CELF-4 Word Classes-Composite	110.13	6.97	85-120
CELF-4 Word Definitions	111.27	7.85	90-125
Age (Years)	21.23	3.82	17.10-38.09
Race (N)	36 Caucasian, 24 African-American, 5 Hispanic, 5 Asian, 5 Mixed Race		

Note: All scores are standard scores (mean = 100, SD = 15) unless otherwise noted.

performance across participants, and as such, those participants were not excluded from the study. To provide descriptive information regarding the sample, participants were classified as having a problem in phonological processing if they scored one or more standard deviations (SD) below the normative mean (i.e., =/<85) on the phonological subtests of the CTOPP and scored within one SD of the normative mean on the core rapid naming composite (letter and number naming) subtests of the CTOPP. Participants were classified as having a problem in naming speed if they scored one or more standard deviations below the normative mean on the RAN subtests of the CTOPP and scored within one SD of the normative mean on the phonological subtests of the CTOPP. Participants who met criteria for both a PA and RAN problem (=/<85 on both RAN and PA composites) were classified as double-deficit (DD), and those who met criteria for neither (RAN and PA composites >85) were classified as unimpaired. Based on this classification scheme, 18 participants had a phonological processing deficit, two had a rapid naming deficit, one had a double-deficit and 40 were unimpaired according to the CTOPP measures. Both participants with rapid naming problems had standard scores on the RAN composite measure equaling 85, and therefore were borderline cases.

Some participants met criteria for a reading disability. Both IQ-discrepancy and low achievement (LA) definitions of RD were utilized. To meet criteria for a reading disability, a participant had either 1) a standard score above 70 on the matrices subtest of the Kaufman Brief Intelligence Test (KBIT; Kaufman & Kaufman, 1990) and a reading regression-corrected discrepancy score one standard error or greater of the estimate or 2) a standard score above 70 on the KBIT and a reading-achievement scaled score at or below 85. Reading achievement measures were assessed with both the Basic Skills composite (word identification and word Attack subtests) and the Total Reading-Short Scale composite (word identification and passage comprehension subtests) of the Woodcock Reading Mastery Test-Revised, Normative Update (WRMT-R/NU, Woodcock, 1998). Seven participants met criteria for a reading disability based on IQ-discrepancy criteria measured using the Basic Skills composite, two met criteria for RD based on IQ-discrepancy criteria measured using the Short Scale composite, and none met criteria for RD based on low-achievement criteria with either measure.

In addition to the CTOPP and WRMT-R/NU, participants were assessed with the Clinical Evaluation of Language Fundamentals (CELF-4; Semel, Wiig, & Secord, 1987) to ensure that no participants met criteria for a language impairment. Participants were given four measures from the CELF-4 (Core Language) that provided a variety of measures across the different domains of language, including the formulated sentences (expressive language and grammar/syntax), word classes (expressive and receptive language), word definitions (receptive language), and recalling sentences (expressive and receptive language combined) subtests. The CELF-4 is normed for persons up to age 21. Some participants ($n = 14$) were older than that age group, and those participants were assessed against the oldest age norms for the CELF-4 per Cirino et al. (2005). Participants evidenced a language impairment if they scored one or more SD below the normative mean (<85) for age on the Core Language composite measure. Based on this classification, no participant met criteria for a language problem. However, several participants had subtest scores 1 SD or more below the normative mean, including one participant on the formulated sentences subtest, and four participants on the recalling sentences measure.

To gain additional descriptive information regarding the sample, each participant completed a background history questionnaire prior to testing. The questionnaire was implemented to gain demographic information and information pertaining to the participants' previous experiences regarding hearing, speech, language, and reading, and also included educational experiences, and questions inquiring about head injuries and other neurologically-based questions. According to the questionnaire, six participants reported being left-handed, and none had any history of hearing or neurological disorders. One participant reported having a history of reading problems. Four participants reported having had an attention problem (although none reported currently taking any medication for attention deficits), and seven participants had a relative with a history of reading problems. Thirty-two participants wore glasses or contact lenses, and none had a cochlear implant or a hearing aid. Six participants had endured extended exposure to loud noises, mainly due to the nature of their employment (e.g., working at the airport), and 12 reported having had multiple ear infections as a child. One participant had taken special education courses, and five had missed weeks or months of school at a time, mainly for minor childhood illnesses. One participant had a history of traumatic brain injury (concussion). A majority of the participants (25) were freshmen; 13 were sophomores, 15 were juniors, and 8 were seniors. Eight participants spoke a second language. Two participants were taking a prescription medication (Lexapro, Loritab).

Stimuli

CMR. A pure-tone signal and two noise maskers were formulated to elicit the maximum masking release as presented in Zettler et al. (in press). The signal stimulus was a 1000-Hz pure tone signal having a 400-ms duration including a 50-ms cosine^2 rise/fall time. The 1000-Hz frequency was selected for the signal frequency as it is commonly used to measure CMR (e.g., Buss, Hall, & Grose, 1997; Hall & Grose, 1990; Veloso et al. 1990), and was consistent with the other masking tasks used in the study. The 400-ms signal duration was used as it has produced maximal CMR on numerous occasions (Hall & Grose, 1990; Schooneveldt & Moore, 1989) with participants obtaining masking releases between 12 and 16 dB. The on-signal masker was a 75 dB(A), 20-Hz wide bandpass noise centered on the signal frequency containing frequencies from 990 Hz to 1010 Hz, that was 100% amplitude modulated at 10 Hz (see Figure 1). Previous research indicated that maximal CMR occurs with narrow noise bandwidths; therefore, the 20-Hz noise bandwidth was used (Schooneveldt & Moore, 1989). Masking release increases when the masker duration exceeds the stimulus duration. For example, Buss et al. (1997) found that participants achieved a masking release of approximately 13 dB when using a 100-ms signal with a 600-ms masker duration, whereas Hall, Grose, and Dev (1997) reported masking releases of approximately 9 dB with a 400-ms signal and a 400-ms masker duration. As the longer masker duration resulted in greater CMR, the 600 ms masker duration was used.

The comodulated masker included the on-signal masker described previously in combination with eight flanking bands comodulated at a rate of 10 Hz (see Figure 2). Each of the flanking bands was 20-Hz wide and was separated from the others by 100 Hz, resulting in flanking bands of 590-610 Hz, 690-710 Hz, 790-810 Hz, 890-910 Hz, 1090-1110 Hz, 1190-1210 Hz, 1290-1310 Hz, and 1390-1410 Hz. Results found by Hall et al. (1990) indicated that a substantial reduction in participants' masking occurred when eight flanking bands were co-modulated with the on-signal band. Additionally, Cohen and Schubert (1987) found that CMR increased for higher levels of stimulation with adult participants attaining a maximum CMR at 75 dB SPL. Therefore, the current study set stimulus noise levels at a maximum of 75 dB SPL including all eight flanking bands.

Masking. Backward and backward-notched masking stimuli replicated those used by Montgomery et al. (2005), Wright et al. (1997) and Zettler (unpublished Master's thesis, 2004) in studies of backward masking in children. In the backward masking condition a 20-ms, 1000-Hz tone was presented 20 ms prior to a 300-ms, 600-1400 Hz bandpass noise, and in the backward

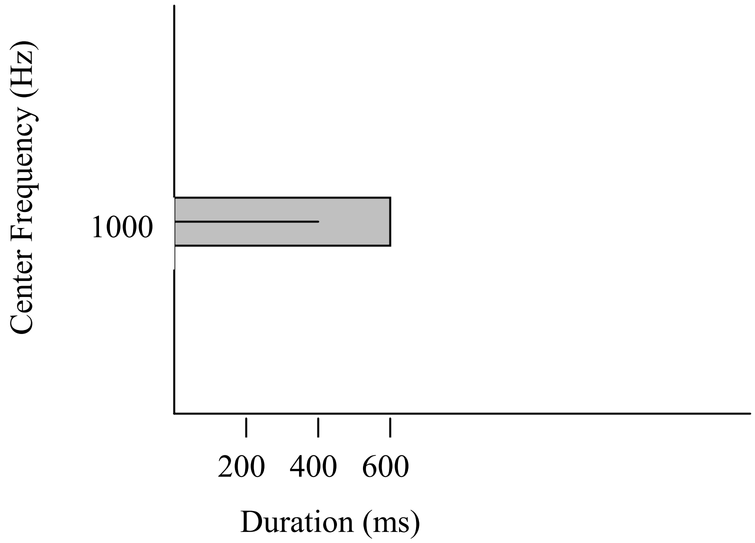

Figure 1. CMR reference condition

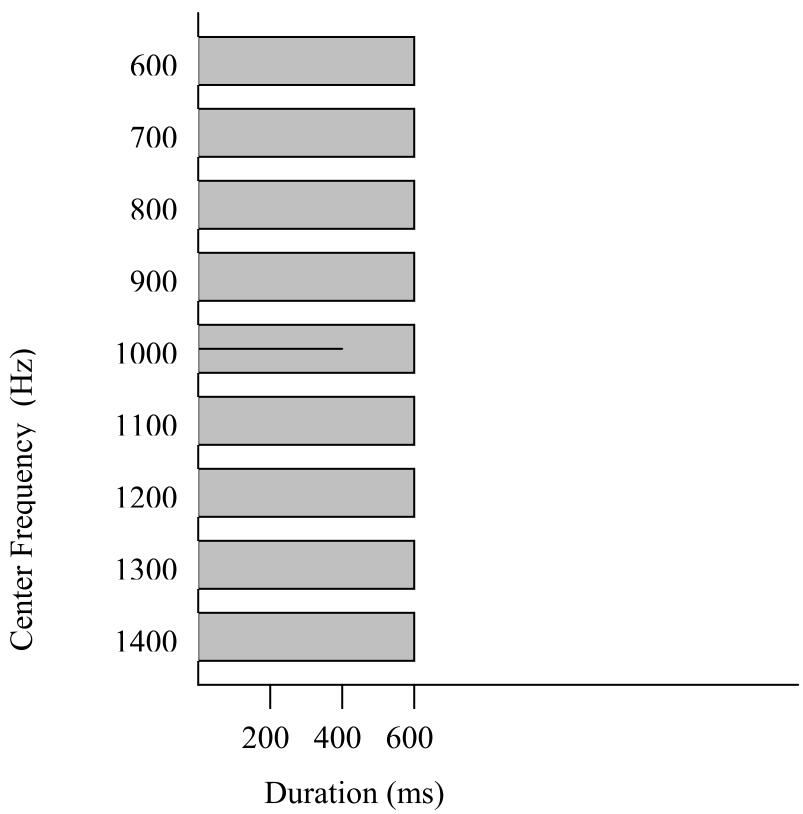

Figure 2. CMR modulated masker condition

masking, notched-noise condition a 1000-Hz tone was presented 20 ms prior to the onset of a 300-ms, 400-1600 Hz bandpass noise containing a spectral notch between 800 and 1200 Hz. The offset of the signal and the onset of the masker occurred at the same time. Masking stimuli had a 10-ms cosine^2 rise/fall time and were presented at 40 dB SPL. Graphical depictions of the backward masking and the backward masking, notched-noise conditions are presented in figures 3 and 4, respectively.

Localization. Localization stimuli replicated those used by Montgomery (unpublished dissertation, 2002). Fourteen-ms clicks were generated and played at sound pressure levels of 18-22 dB(A), over the ambient noise level of the room in which testing is conducted, approximately 50 dB(A). Delays between the clicks presented across the loudspeakers in the dual source conditions were 5, 10, 20, 50, 100, 200, and 400 ms.

Apparatus and Stimulus Generation

Participants were tested in a double-walled sound-attenuated room in the author's university where each participant was seated at a table in front of a portable computer. The ambient noise level in the laboratory was 28 dB(A).

Auditory Masking Paradigms. A custom-software program digitized the signals and maskers for CMR and backward masking stimuli with a 20-kHz sampling rate using a Tucker-Davis Technologies (TDT) Array Processor Board. The signal and maskers were sent through a TDT 16-bit D/A converter, low-pass filtered at 10 kHz, routed through a TDT programmable attenuator, and then summed before being sent through a headphone buffer. Participants listened to the sounds via Sennheiser HD 25-1 headphones. Because Cohen and Schubert (1987) found approximately 1.5 dB more masking release when presenting sounds diotically relative to monotically, stimuli were presented diotically for the CMR paradigm in the current study.

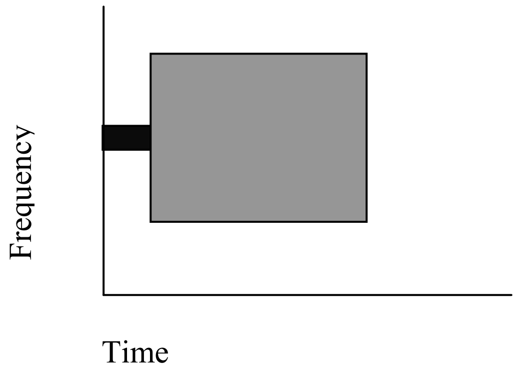

Figure 3. Backward masking bandpass condition.

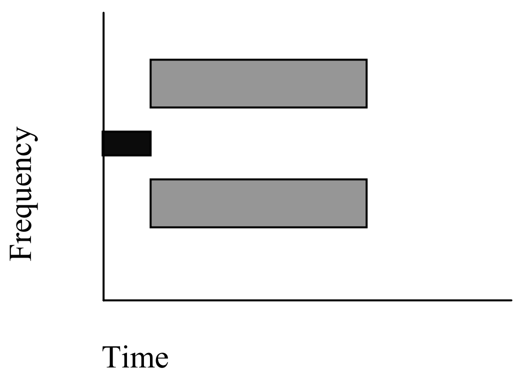

Figure 4. Backward masking, notched-noise condition

Masking stimuli were presented monaurally to the left ear, as stimuli also were presented monaurally by Montgomery et al. (2005), Wright et al. (1997), and Zettler (unpublished Master's thesis, 2004).

Localization. A TDT custom software program generated and digitized at 20 kHz the stimuli that were sent through a TDT digital to analog converter and two programmable attenuators. Clicks were presented through either one or both of two powered Bose loudspeakers at a rate of 1.5/s.

Motor speed. The finger tapping apparatus consisted of a board with a lever and an attached counter. Participants pressed the lever while resting their hand on the board. The counter took a count of the total number of finger taps in a 10s period of time.

Procedure

CMR stimuli were presented prior to backward masking, backward masking notched-noise stimuli, and localization stimuli, as the latter tasks required the fewest number of trials to complete, and therefore were relatively less taxing to the participant's attentional state than the CMR tasks. Once the auditory testing was completed, participants were administered the finger tapping task, CTOPP, WRMT-R/NU, and CELF-4. Participants completed the test battery within 2 ½ to 3 hours**.**

CMR. Two conditions were presented to each participant: one condition consisted of the signal plus the on-signal masker ("reference condition"), and the other condition consisted of the signal and the masker containing flanking bands ("modulated masker condition"). The order of presentation for the two conditions was counterbalanced across participants with equal numbers randomly assigned to receive either the reference condition or the modulated masker condition first. In both conditions, three threshold estimates were obtained for all participants unless the first two thresholds obtained were within 5 dB of one another. An average threshold was calculated for each participant in each condition and the difference between the averages of the reference and modulated-masker conditions was taken as the estimate of CMR.

Participants were tested with a single-interval maximum likelihood (ML) procedure (Green, 1993). The ML procedure produces threshold estimates similar to those obtained with forced choice procedures (Gu & Green, 1994), but threshold values calculated using ML can be obtained more rapidly and efficiently so attentional factors have minimal impact on performance. The ML algorithm determines the psychometric function having the maximum probability of being the listener's "true" function based on the participant's response to each trial. A psychometric function is an S-shaped function that illustrates the proportion of "Yes" responses on the Y-axis as a function of signal level (dB) on the X-axis. The ML algorithm requires setting several parameters to guide the calculation of hypothetical psychometric functions, including the range of stimulus levels, the step size (i.e., the spacing of possible stimuli within the range of levels), and the false alarm rate. The current study used an 80-dB range of stimuli with a 1-dB step size and false alarm rates of 0.0, 0.1, 0.2, and 0.3. Gu and Green (1994) used these four false alarm values to implement a wide range of possible psychometric functions, thereby providing a more accurate estimate of the listener's threshold. Using a 1-dB step size afforded values along the X-axis ranging from 14-24 dB to 95-100 dB in 1 dB steps (e.g., 24, 25, 26, etc.). These parameters produced approximately 244 hypotheses.

The first trial presented a stimulus level between 95 and 100 dB for which it was assumed that all normal hearing listeners would be able to hear the tone within the noise masker, and the second trial presented the 24-dB stimulus level for which it was assumed that all normal hearing listeners would not be able to hear the tone within the 75-dB noise masker. A hypothetical set of psychometric functions was calculated by the computer based on the participant's responses to these first two trials, and the 60% correct point on the psychometric function having the maximum likelihood was selected to provide the stimulus level for the next trial. After each trial, a new set of psychometric functions was calculated, and the stimulus level for the next trial was selected from the function having the maximum likelihood. Across trials, the psychometric function having the maximum likelihood varied and more closely reflected the listener's true performance. The listener's threshold was extrapolated at the 71% point on the psychometric function having the maximum likelihood at the end of testing. Variability and bias in the threshold estimate decrease as the number of trials increases (Gu & Green, 1994). Therefore, each threshold estimate was based on 24 trials in each of the two conditions including 6 "catch" trials specifically designed to reduce any false alarm bias inherent in the design (Gu & Green, 1994). Stimuli on catch trials were at the 14-dB stimulus level, and were randomly interspersed among the "true" trials. Based on Gu and Green's (1994) simulations, the number of trials should provide a reliable estimate of the listener's true threshold.

The inter-trial interval was a minimum of 300 ms. If the participant failed to respond to the stimulus on a trial within 5s, the program prompted the listener to select an option. Therefore, the inter-trial interval varied from trial to trial. After each threshold estimate, the participant was rewarded with a 30-55s audiovisual reinforcer that consisted of edited clips of Disney films.

Prior to testing in each condition, listeners received a demonstration of the task and an opportunity to practice it. The experimenter asked the participant to listen carefully to each trial, to decide whether a tone was presented, and to press one button on the computer keyboard when a "beep" was heard and another button when a beep was not heard. Several trials for each of three practice stimuli were presented: a 90-dB tone, a 90-dB tone with the noise masker, and the noise masker alone. First, the experimenter demonstrated the 90-dB tone and told the participant "this is the sound you will be listening for in a noise." After the 90-dB practice sounds were played, the experimenter explained that the noise would now be presented alone, and that whenever the participant heard this sound the response should always be "no" because there was no beep in this sound. Finally, the participant was instructed to listen to the beep now heard with the noise. The participant was told, "This sound will always be a 'yes,' because you can hear the beep in the noise. Can you hear the beep?" If the participant either verbally confirmed hearing the beep in the noise, or responded correctly to the practice trials on the keyboard, training was complete and the ML procedure began. If the participants did not respond correctly to the practice trials using the keyboard, suggesting that they did not understand the task, training continued and stimuli were presented separately as outlined above until the participants stated or responded that they understood. After the completion of practice stimuli, the ML procedure began.

Masking. Procedures used for masking replicated those used in Zettler et al. (in press). Participants were assigned to receive either the backward masking condition or the backward masking-notched condition first, and the order of presentation was counterbalanced across participants. The training and instructions given to the participants were the same as in the CMR paradigm. Participants received 16 trials, including five control trials, in a single-interval, yes/no maximum-likelihood procedure as described previously for the CMR task. The first trial presented the maximum stimulus level between 95 and 100 dB, and the second trial presented the minimum stimulus level of 14-24 dB. Participants were required to respond correctly to the first two trials for the ML procedure to begin. The inter-trial interval varied with the speed of each participant's response, but was always a minimum of 300 ms. False alarm rates included 0.0, 0.1, 0.2, and 0.3 with a 1-dB step size. These parameters produced approximately 244 hypotheses. Threshold was taken as the 71% correct point on the final psychometric function. Three threshold estimates were obtained unless participants had two estimates within 5 dB. After each threshold estimate, the participant was shown a 30s-55s edited clip of various Disney films as audiovisual reinforcement.

Localization. Stimuli were presented to the participant through the two loudspeakers. Speakers were placed three feet apart at 90° from the listener's midline while seated at the portable computer. A single-source condition and a set of dual-source conditions were presented to the listener. In the single-source condition, clicks were presented from one of two loudspeakers. The listener indicated the direction of the clicking sound. In the dual source condition, clicks were presented from both loudspeakers with one sound delayed relative to the other and the participant was instructed to indicate the direction of the first sound.

Participants had an opportunity to practice sound source identification in both conditions for 10 trials prior to active testing. In the single source condition, listeners listened to clicks presented through one of the two speakers and pressed either the right or left arrow key on the computer keyboard to indicate the direction of the click. A 5s visual reinforcement followed each correct response. A recorded voice instructing the participant to "listen for the next sound" was played when the listener made an incorrect response. In both conditions, the participant was required to respond correctly to four out of five practice trials prior to actual testing.

During testing, the participant listened to 80 trials, which consisted of both single-source trials and dual-source trials at each delay. Ten single-source trials and ten trials in the dual-source condition for each delay were presented. Trial order was randomized and counterbalanced across speakers.

Motor speed. Participants first were instructed to place their dominant hand on the board and to press the lever with their index finger until the counter changed. After several practice trials, the participant was instructed to tap as many times as possible for 10s. The total number of taps was recorded by the counter. The process then was repeated for the non-dominant hand, with trials alternating between the dominant and non-dominant hands. The task was repeated for five times with each hand unless the trials differed by more than 5 taps, in which case two more 10s trials were given. The mean of all five trials was taken as a measure of motor speed unless seven trials were administered. If seven trials were given, the highest and lowest scores were omitted and the mean was taken from the remaining five trials, according to the method set forth in Ruff and Parker (1993). The average for both hands was then taken as the measure of motor speed. Finally, a laterality index was calculated to provide a measure of hemispheric dominance for the motor task. The index was calculated by subtracting the average score for the left hand from the average score of the right hand and dividing the difference by the sum of the average number of taps for both the right and left hands.

Chapter 3: Results

Data Screening

All variables first were examined for outliers, violations of regression assumptions and skewness. A number of outliers 3 SD or greater from the sample mean were discovered. One participant had an especially low number of finger taps for both hands, and fell outside of three standard deviations from the mean. This participant also had a temporal order judgment threshold outside of 4 SD from the mean. This finding is noteworthy in that this participant had an immediate family member who had RD, although the participant had average scores on the reading and language measures. Another participant had an average finger taps score that was 3 SD above the mean. Two participants had a laterality index greater than 3 SD from the mean. One participant had an especially low raw score (2) on the blending test, and fell outside of 4 SD from the mean. Another participant had a NVIQ score of 129 and fell outside of 3 SD greater than the rest of the sample. This participant spent considerably more time than did others in providing responses to the stimuli, which may have been responsible for the higher score on this measure relative to the rest of the sample. As the K-BIT is a non-timed measure, this possibility cannot be evaluated with the available data. This person also was an outlier on the formulated sentences subtest. One participant had a word identification score that was 4 SD greater than the mean, which caused the Basic Skills and Total Reading-Short Scale values to also be outliers for this participant. One participant had a Core Language score that was greater than 3 SD lower than the sample mean. However, this person’s score was a 98. Because the sample’s mean language scores were quite high, this relatively low score became an outlier. This person’s scores subsequently were outliers for the formulated sentences and word classes- expressive subtests. Two participants scored more than 3 SD below the mean on the word classes-receptive measure, and one of these also had a score that was an outlier on the expressive measure. One participant showed CMR that was an outlier relative to the other participants. This result appeared to be due to the reference condition thresholds being above average (poorer performance) and the modulated masker condition thresholds being below average (better performance) for that person, causing a large CMR. One participant was significantly older (38 years, + 4 SD). Many of these participants had extreme values on multiple measures. Eight participants (six were not outliers on any other measure) had no measurable threshold on the measure of temporal order judgment (TOJ) given. For these participants, their average threshold never dropped below 80%. As threshold was measured at 70.9%, these participants were dropped pairwise from all TOJ analyses resulting in n = 67 for this outcome measure.

Durbin-Watson statistics indicated that the regression assumption concerning autocorrelation was met. Examination of the correlation matrix revealed that the independent variables were not correlated, suggesting that the regression assumption of multicollinearity also was met. Finally, an examination of scatterplots of the residual error terms revealed that the regression assumption of homoskedasticity was not violated.

Several variables showed skewness suggesting a non-normal distribution. As a result, the decision about retaining outliers was made after variable skewness was addressed. Age and word identification were positively skewed. Average finger taps-dominant hand, laterality index, average motor speed, elision, blending, the elision and blending (phonological composite), core language, formulated sentences, word classes-expressive, word classes- receptive, word classes-total, and recalling sentences were all negatively skewed. Square root transformations were used to address positive and reflect and square root transformations were used to address negative skewness in the affected variables, except for the laterality index, which was severely skewed and transformed with the reflect and inverse method per Tabachnick and Fiddell (1989). After transformation, no variables remained skewed with the exception of the laterality index, which remained slightly negatively skewed. Transformation also changed the status of many of the outliers, resulting in many of the outliers no longer qualifying as outliers among the predictor variables. However, the one participant who was an outlier on the measure of NVIQ was retained in the data set, as removing this participant from the analyses caused the NVIQ measure to become skewed. The two participants who qualified as outliers for the laterality index remained outliers after transformation. However, they were retained in the data set. After transformation, these participants were only slightly more than 3 SD from the mean. In addition, both of these participants were left-handed, possibly explaining why they were outliers relative to the predominantly right-handed data set. Removing these participants would have resulted in only four left-handed participants in the data set, an already under-represented subset of the sample. For these reasons, these two participants were retained. Conversely, the one participant who was an outlier on the measure of average motor speed continued to fall well outside of 3 SD from the mean after transformation. It is possible, but unknown, whether or not this person performed the task correctly. That is, although all participants were instructed to leave their wrists on the board while tapping the lever with the index finger, lifting the wrist results in greater leverage and allows one to tap faster. As it is not clear whether or not this participant carefully followed the directions (potentially explaining the greater number of finger taps relative to the other participants in the sample), this participant was omitted from the data set. The predictor and descriptive variables that were skewed are reported in their transformed form in the correlation matrix and in the regression analyses.

Descriptive Statistics

CMR. To determine whether the order of presentation of the auditory variables significantly influenced performance, an analysis of variance (ANOVA) was conducted for both comodulation masking release threshold conditions with order as the between subjects factor and threshold as the within subjects factor. ANOVA for the thresholds in the CMR paradigm indicated that order of presentation did not significantly influence performance ($p > .05$) in the full data set, suggesting that participants who received the reference condition first did not show thresholds that differed significantly from participants who received the modulated masker condition first. The mean reference condition threshold for the sample was 63.98 dB(A). The mean modulated masker condition threshold was 54.35 dB(A), resulting in a mean CMR for the sample of 9.63 dB. Additional descriptive statistics for all auditory measures are provided in Table 2.

Masking. ANOVA for backward masking thresholds indicated that order of presentation also did not significantly influence performance ($p > .05$), suggesting that participants who received the backward masking condition first did not show thresholds that differed significantly from those of participants who received the backward masking notched noise condition first. The mean backward masking threshold was 48.07 dB(A), and the mean backward masking threshold in the notched-noise condition was 46.32 dB(A).

Localization. ANOVA revealed that the expected quadratic trend of performance was demonstrated in the sample ($F(1,74)= 336.12$, $p < .01$), with participants achieving a high level of performance in the single-source condition, dropping at the short delays, and then improving again at the longest delays presented (400 ms). The mean TOJ threshold was 43.48 ms, and the mean overall percent correct for localization was 85.08. Descriptive statistics for performance in each delay condition are presented in Table 3. Pearson Product-Moment correlations between the

Table 2

Descriptive Statistics for the Auditory Measures

Measure	Mean	SD	Range
CMR Reference	63.98	12.89	38.06- 97.06
CMR Modulated Masker	54.35	8.57	35.73- 73.70
CMR	9.63	14.07	-20.96- 54.24
Backward Masking	48.07	11.22	26.76- 81.15
Backward Masking-Notched Noise	46.32	10.72	22.80- 70.20
Temporal Order Judgment Threshold*	43.48	27.90	5.15-176.88
Localization Overall Percent Correct	85.08	6.53	68.80- 96.20

* n = 67

Table 3

Descriptive Statistics for Localization Delays

Delay	Mean	SD	Range
Single Source	99.87	1.15	90-100
5-ms Delay	72.27	15.99	30-100
10-ms Delay	73.73	17.77	40-100
20-ms Delay	64.93	17.73	30-100
50-ms Delay	76.67	16.55	30-100
100-ms Delay	94.40	9.90	40-100
200-ms Delay	98.80	4.64	70-100
400-ms Delay	99.87	1.15	90-100

auditory, reading, language, and motor variables are presented in Table 4. For the transformed variables that were also reflected, the interpretation of the correlation is of the opposite sign. For example, if the sign of the correlation is negative for a reflected transformed variable, then the interpretation is made as though the sign were positive.

Regression Analyses-Naming Speed

CMR. Standardized regression coefficients and R^2 values for each naming speed regression are presented in Table 5. Hierarchical multiple regression analyses were conducted for each of the auditory dependent measures, with NVIQ, phonological composite, and naming speed entered as predictors into the regression equation. For reference condition thresholds, none of the predictors significantly influenced reference condition thresholds, and the overall model was not significant ($R^2 = .086$, $F(3,71) = 2.217$, $p > .05$). Alternatively, regression analyses indicated that NVIQ predicted performance in the modulated masker condition ($R^2 = .162$, $F(1,73) = 14.110$, $p < .01$). The inclusion of the phonological processing composite entered second approached, but did not attain, significance ($\Delta R^2 = .034$, $p = .08$), yet the model remained significant ($R^2 = .196$, $F(2,72) = 8.753$, $p < .01$). Likewise, the inclusion of the RAN letters and numbers composite also was not significant ($\Delta R^2 = .000$, $p > .05$), but the overall model remained so ($R^2 = .196$, $F(3,71) = 5.759$, $p < .01$). CMR was not predicted by any step of the model, and the overall model was not significant ($R^2 = .038$, $F(3,71) = .942$, $p > .05$).

Masking. Backward masking was predicted by NVIQ ($R^2 = .053$, $F(1,73) = 4.076$, $p < .05$). The phonological composite was not significant, yet the overall model remained so ($R^2 = .084$, $F(2,72) = 3.317$, $p < .05$). RAN failed to predict performance, and the overall model became non-significant ($R^2 = .085$, $F(3,71) = 2.192$, $p > .05$). In the backward masking, notched-noise condition, NVIQ again predicted performance $R^2 = .085$, $F(1,73) = 6.751$, $p < .05$). Neither

Table 4

Correlations between the Auditory, Reading, and Language Variables (TOJ n = 67)

Variable	NVIQ	2	3	4	5	6	7	8	9	10	11
2. Laterality Index	-.003										
3. Average Motor Speed	-.281[a]	.070									
4. Elision	-.325[b]	-.045	.254[a]								
5. Blending	-.347[b]	-.008	.127	.560[b]							
6. Phonological Composite	-.373[b]	-.013	.224	.903[b]	.852[b]						
7. RAN Comp (letters, numbers)	.125	-.021	-.165	-.141	-.048	-.108					
8. RAN Comp (colors, objects)	.037	-.031	-.050	-.168	-.102	-.145	.404[b]				
9. Word ID	.220	.161	-.219	-.480[b]	-.422[b]	-.514[b]	.251[a]	.132			
10. Word Attack	.354[b]	.254[a]	-.296[b]	-.398[b]	-.322[b]	-.402[b]	.249[a]	.066	.607[b]		
11. Passage Comprehension	.422[b]	.078	-.161	-.391[b]	-.477[b]	-.482[b]	-.024	.087	.554[b]	.599[b]	
12. Basic Skills	.325[b]	.226	-.308[b]	-.464[b]	-.370[b]	-.471[b]	.309[b]	.098	.894[b]	.875[b]	.596[b]
13. Total Reading-Short Scale	.372[b]	.133	-.266[a]	-.490[b]	-.462[b]	-.536[b]	.175	.098	.903[b]	.712[b]	.829[b]
14. Core Language	-.272[a]	.029	.073	.417[b]	.338[b]	.422[b]	.133	-.046	-.287[a]	-.299[b]	-.488[b]
15. Formulated Sentences	-.047	. 159	.026	.187	.255[a]	.256[a]	.093	-.077	-.130	-.120	-.266[a]
16. Word Classes-Expressive	-.350[b]	-.022	.023	.350[b]	.316[b]	.365[b]	.106	.067	-.194	-.265[a]	-.335[b]
17. Word Classes-Receptive	-.267[a]	.051	-.182	.168	.199	.186	.083	.053	-.125	-.054	-.326[b]
18. Word Classes-Composite	-.319[b]	.023	-.060	.253[a]	.228[a]	.257[a]	.112	.127	-.174	-.206	-.342[b]
19. Recalling Sentences	-.013	.087	.171	.268[a]	.171	.256[a]	.029	-.134	-.206	-.258[a]	-.262[a]
20. Word Definitions	.337[b]	.110	-.087	-.391[b]	-.214	-.333[b]	-.043	.009	.319[b]	.320[b]	.430[b]
21. Reference Condition	-.152	-.091	.205	.151	.243[a]	.218	.148	-.103	-.173	-.156	-.242[a]
22. Modulated Masker	-.402[b]	-.043	.396[b]	.285[a]	.280[a]	.320[b]	-.051	.093	-.259[a]	-.326[b]	-.336[b]
23. CMR	.106	-.057	-.054	-.035	.052	.005	.166	-.151	-.001	.056	-.017
24. Backward Masking	-.230[a]	-.199	.378[b]	.240[a]	.219	.250[a]	-.020	.070	-.194	-.370[b]	-.247[a]
25. Backward Masking-Notched	-.291[a]	-.130	.339[b]	.170	.228[a]	.212	-.044	-.009	-.237[a]	-.386[b]	-.288[a]
26. TOJ Threshold	-.183	-.105	.175	.075	.178	.144	-.147	-.048	-.269[a]	-.074	-.061
27. Percent Correct- 5-ms Delay	-.014	-.053	.140	.075	.119	.089	.011	.054	-.062	-.089	-.073
28. Percent Correct- 400-ms Delay	.005	-.242[a]	-.008	-.006	.153	.061	-.111	-.093	-.036	-.138	-.014

[a] = p < .05, [b] = p < .01

Table 4 (continued)

Correlations between the Auditory, Reading, and Language Variables- With Outliers (TOJ n = 67)

Variable	12	13	14	15	16	17	18	19	20	21
2. Laterality Index										
3. Average Motor Speed										
4. Elision										
5. Blending										
6. Phonological Composite										
7. RAN Comp (letters, numbers)										
8. RAN Comp (colors, objects)										
9. Word ID										
10. Word Attack										
11. Passage Comprehension										
12. Basic Skills										
13. Total Reading-Short Scale	.890[b]									
14. Core Language	-.296[b]	-.417[b]								
15. Formulated Sentences	-.114	-.184	.611[b]							
16. Word Classes-Expressive	-.244[a]	-.288[a]	.693[b]	.239[a]						
17. Word Classes-Receptive	-.084	-.214	.589[b]	.228[a]	.641[b]					
18. Word Classes-Composite	-.199	-.270[a]	.650[b]	.245[a]	.905[b]	.850[b]				
19. Recalling Sentences	-.243[a]	-.283[a]	.605[b]	.312[b]	.086	.037	.027			
20. Word Definitions	.332[b]	.417[b]	-.703[b]	-.202	-.607[b]	-.392[b]	-.504[b]	-.158		
21. Reference Condition	-.164	-.225	.301[b]	.192	.264[a]	.024	.167	.129	-.244[a]	
22. Modulated Masker	-.321[b]	-.353[b]	.251[a]	.195	.148	.167	.168	.164	-.083	.188
23. CMR	.045	.009	.123	.056	.152	-.079	.051	.018	-.173	.802[b]
24. Backward Masking	-.295[a]	-.247[a]	.260[a]	.182	.170	.167	.184	.148	-.169	.082
25. Backward Masking-Notched	-.334[b]	-.289[a]	.244[a]	.099	.192	.154	.185	.137	-.173	.258[a]
26. TOJ Threshold	-.175	-.186	.053	.081	-.136	-.133	-.158	.053	-.082	.167
27. Percent Correct- 5-ms Delay	-.111	-.069	.028	.040	.082	-.052	.075	-.011	-.109	.014
28. Percent Correct- 400-ms Delay	-.135	-.060	.025	.023	.008	-.021	-.020	.108	.093	.068

[a] = $p < .05$, [b] = $p < .01$

Table 4 (continued)

Correlations between the Auditory, Reading, and Language Variables (TOJ n = 67)

Variable	22	23	24	25	26	27
2. Laterality Index						
3. Average Motor Speed						
4. Elision						
5. Blending						
6. Phonological Composite						
7. RAN Comp (letters, numbers)						
8. RAN Comp (colors, objects)						
9. Word ID						
10. Word Attack						
11. Passage Comprehension						
12. Basic Skills						
13. Total Reading-Short Scale						
14. Core Language						
15. Formulated Sentences						
16. Word Classes-Expressive						
17. Word Classes-Receptive						
18. Word Classes-Composite						
19. Recalling Sentences						
20. Word Definitions						
21. Reference Condition						
22. Modulated Masker						
23. CMR	-.437[b]					
24. Backward Masking	.533[b]	-.249[a]				
25. Backward Masking-Notched	.487[b]	-.061	.787[b]			
26. TOJ Threshold	.066	.111	.107	.291[a]		
27. Percent Correct-5-ms Delay	.027	-.003	.118	.089	-.196	
28. Percent Correct- 400-ms Delay	.057	.027	.032	.031	.118	.163

[a] = $p < .05$, [b] = $p < .01$

Table 5

Hierarchic Multiple Regression Statistics for Naming Speed

	Standardized partial regression coefficients (β) for variables in the equations		
	Step 1	Step 2	Step 3
Condition	NVIQ	Phonological Composite (PP)	RAN
Reference	-.152	.187	.182
Modulated Masker	-.402 [b]	.198	.012
CMR	.106	.051	.159
Backward Masking (BM)	-.230 [a]	.191	.021
BM, Notched-Noise	-.291 [a]	.121	.000
Temporal Order Judgment	-.183	.093	-.127
Percent Correct, 5-ms	-.014	.098	.019
Percent Correct, 400-ms	.005	.073	-.109

	Proportion of variance accounted for (R^2) by variables in the equations (ΔR^2 in parentheses)		
	Step 1	Step 1+2	Step 1+2+3
Condition	NVIQ	NVIQ, PP	NVIQ, PP, RAN
Reference	.023 (.023)	.053 (.030)	.086 (.032)
Modulated Masker	.162[b] (.162)[b]	.196 [b](.034)	.196[b](.000)
CMR	.011 (.011)	.013 (.002)	.038 (.025)
BM	.053[a] (.053)[a]	.084[a] (.031)	.085 (.000)
BM, Notched-Noise	.085[a] (.085)[a]	.097[a] (.013)	.097 (.000)
Temporal Order Judgment	.034 (.034)	.041 (.008)	.057 (.016)
Percent Correct, 5-ms	.000 (.000)	.008 (.008)	.009 (.000)
Percent Correct, 400-ms	.000 (.000)	.005 (.005)	.016 (.012)

[a] $p < .05$
[b] $p < .01$

the phonological composite ($\Delta R^2 = .013$, $p > .05$) nor the RAN composite ($\Delta R^2 = .000$, $p > .05$) predicted performance, and the overall model became non-significant ($R^2 = .097$, $F(3,71) = 2.547$, $p > .05$).

Localization. Three dependent localization measures were used in the regression equations. TOJ threshold- the minimum amount of delay that participants can "tolerate" and still successfully indicate the temporal order between two sounds- was used as one dependent localization measure. As a measure of the precedence effect, 5-ms delay performance was used as a dependent measure, and as an additional measure of temporal order judgment, the 400-ms delay condition was used as a dependent measure. TOJ thresholds were not predicted by any step of the model, and the overall model was not significant ($R^2 = .057$, $F(3,63) = 1.276$, $p > .05$). The regression model also failed to predict percent correct, 5-ms delay performance at any step of the model, and the overall model was not significant ($R^2 = .009$, $F(3,71) = .209$, $p > .05$). Percent correct, 400-ms delay performance also was not predicted by any step of the model, and the overall model was not significant ($R^2 = .016$, $F(3,71) = .393$, $p > .05$).

Regression Analyses-Motor Speed

CMR. Standardized regression coefficients and R^2 values for each regression are presented in Table 6. Regression analyses were conducted for reference and modulated masker thresholds and CMR, with NVIQ, laterality ratio, and average motor speed entered as predictors into the regression equation. As the phonological processing composite did not significantly predict auditory processing in the regression equations for naming speed, it was dropped from the regression equations for motor speed. For reference condition thresholds, no step in the model predicted performance, and the overall model was not significant ($R^2 = .062$, $F(3,71) = 1.575$, $p > .05$). NVIQ continued to predict modulated masker thresholds ($R^2 = .162$, $F(1,73) =$

Table 6

Hierarchic Multiple Regression Statistics for Motor Speed

	Standardized partial regression coefficients (β) for variables in the equations		
	Step 1	Step 2	Step 3
Condition	NVIQ	Laterality Index	Motor Speed
Reference	-.152	-.091	.184
Modulated Masker	-.402[b]	-.045	.312[b]
CMR	.106	-.056	-.022
Backward Masking (BM)	-.230[a]	-.200	.357[b]
BM, Notched-Noise	-.291[a]	-.131	.291[a]
TOJ	-.183	-.109	.147
Percent Correct, 5-ms	-.014	-.053	.153
Percent Correct, 400-ms	.005	-.242[a]	.011

	Proportion of variance accounted for (R^2) by variables in the equations (ΔR^2 in parentheses)		
	Step 1	Step 1+2	Step 1+2+3
Condition	NVIQ	NVIQ,LI	NVIQ, LI, MS
Reference	.023 (.023)	.031 (.008)	.062 (.031)
Modulated Masker	.162[b](.162)[b]	.164[b](.002)	.253[b](.089)[b]
CMR	.011 (.011)	.014 (.003)	.015 (.000)
BM	.053[a](.053)[a]	.093[a] (.040)	.210[b](.117)[b]
BM, Notched-Noise	.085[a](.085)[a]	.102[a] (.017)	.179[a](.077)[a]
TOJ	.034 (.034)	.045 (.012)	.066 (.020)
Percent Correct, 5-ms	.000 (.000)	.003 (.003)	.024 (.021)
Percent Correct, 400-ms	.000 (.000)	.058 (.058)[a]	.058 (.000)

[a] $p < .05$
[b] $p < .01$

14.110, $p < .01$). The addition of the laterality ratio was not significant ($\Delta R^2 = .002$, $p > .05$), but the overall model remained so ($R^2 = .164$, $F(2,72) = 7.061$, $p < .01$). The addition of average motor speed was significant ($\Delta R^2 = .089$, $F(1,71) = 8.495$, $p < .01$), and the overall model remained highly significant ($R^2 = .253$, $F(3,71) = 8.029$, $p < .01$). CMR was not predicted by any step of the model, and the overall model was not significant ($R^2 = .015$, $F(3,71) = .355$, $p > .05$).

Masking. Regression analyses were conducted for backward masking and backward masking, notched-noise thresholds, with NVIQ, laterality ratio, and average motor speed entered as predictors into the regression equation. Regression analyses conducted for backward masking revealed that NVIQ continued to predict thresholds ($R^2 = .053$, $F(1,73) = 4.076$, $p < .05$). The laterality ratio did not attain significance ($\Delta R^2 = .040$, $F(1,72) = 3.165$, $p > .05$), yet the overall model remained significant ($R^2 = .093$, $F(2,72) = 3.681$, $p < .05$). The addition of average motor speed was significant ($\Delta R^2 = .117$, $F(1,71) = 10.510$, $p < .01$), and the overall model was highly significant ($R^2 = .210$, $F(3,71) = 6.281$, $p < .01$). Regression analyses conducted for backward masking, notched-noise revealed that NVIQ continued to predict performance ($R^2 = .085$, $F(1,73) = 6.751$, $p < .05$). The inclusion of the laterality index was not significant ($\Delta R^2 = .017$, $p > .05$), yet the overall model remained so ($R^2 = .102$, $F(2,72) = 4.084$, $p < .05$). The inclusion of average motor speed was significant ($\Delta R^2 = .077$, $F(1,71) = 6.690$, $p < .05$), and the overall model remained so ($R^2 = .179$, $F(3,71) = 5.168$, $p < .01$).

Localization. Regression analyses conduced for TOJ thresholds revealed that no step in the model attained significance, and the overall model was not significant ($R^2 = .066$, $F(3,63) = 1.472$, $p > .05$). Regression analyses conducted for 5-ms delay indicated that no step in the model was significant, and the overall model did not reach significance ($R^2 = .024$, $F(3,71) = .592$, $p > .05$). Regression conducted for 400-ms delay revealed that NVIQ did not predict performance, and the overall model was not significant ($R^2 = .000$, $F(1,73) = .002$, $p > .05$). However, the inclusion of the laterality index was significant ($\Delta R^2 = .058$, $F(1,72) = 4.460$, $p < .05$), but the overall model was not significant ($R^2 = .058$, $F(2,72) = 2.231$, $p > .05$). The inclusion of average motor speed was not significant ($\Delta R^2 = .000$, $F(1,71) = .008$, $p > .05$), and the overall model was not significant ($R^2 = .058$, $F(3,71) = 1.469$, $p > .05$).

Chapter 4: Discussion

The present results contribute to the understanding of auditory processing by examining two of the factors (naming speed and motor speed) that influence performance in three complex auditory tasks (CMR, backward masking, and localization). In so doing, this research contributes to the larger domain of understanding how auditory processing influences language and reading, and explains why some of the disparities across studies measuring auditory processing in individuals with reading and language impairments may occur. In addition, this study provides data on the largest known sample with adults on three different auditory tasks. As traditional psychoacoustics research often tests relatively small samples, this study contributes to the understanding of CMR, backward masking, and localization processing with a much larger group of naïve adult listeners than has been previously reported.

The sample, drawn from a population of university undergraduates, proved to be unexpectedly complex and heterogeneous with numerous outliers and skewed variables. After transformation, all but one of the skewed variables (laterality index) were normalized, yet some outliers remained. The presence or absence of the outliers had differential effects on the results of the analyses. The decision to retain those that were retained in the data set was based in part on how their absence would impact the remaining data for that variable, and thus interpretations about the data are made cautiously. Future research should assess how well the results will generalize to other samples.

One of the two hypotheses addressed in the present study was supported partially, with timing tasks predicting auditory thresholds for some but not all of the auditory measures used. Hypothesis 1, suggesting that naming speed would predict auditory temporal thresholds, was not supported as RAN did not predict thresholds for any of the auditory measures assessed after a majority of the outliers were removed from the data set. This lack of a significant finding is indicated also in the correlation matrix, which showed that none of the auditory measures correlated significantly with either naming speed measure (letters/numbers or colors/objects), suggesting that these abilities may have unique underlying timing components.

Hypothesis 2, suggesting that motor speed would predict auditory temporal thresholds, was supported partially, with motor speed predicting thresholds for the modulated masker condition of CMR and both backward masking conditions. Thus, the influence of timing, measured by motor speed, was found both in CMR and in the backward masking tasks, suggesting that the processes of auditory temporal processing and timing are not completely independent. Although the influence of timing was evidenced in CMR and backward masking, it was not found in the present sample in the perception of the precedence effect or in TOJ thresholds. However, the motor laterality index did predict performance in the TOJ task at the 400-ms delay, but not at 5 ms. These results indicate that those individuals who are more lateralized tended to perform better on the measure of TOJ, having a higher percent correct at 400 ms than those who were less lateralized. Conversely, lateralization did not impact the precedence effect. As indicated in previous research with children (Zettler et al., in press), NVIQ continued to predict thresholds in the modulated masker condition of CMR, as well as for backward masking and backward masking, notched-noise thresholds. Unlike (Zettler et al., in press), however, NVIQ failed to predict thresholds in the reference condition, indicative of the developmental differences across the samples in the two studies.

Average motor speed correlated with elision as well as the word attack subtest, Basic Skills composite, and Total Reading, Short Scale composite of the WRMT-R/NU ($p < .05$), supporting previous research suggesting that motor speed is linked to reading ability (Wolff, 2002). The present study extends this research to include auditory temporal processing by demonstrating significant relationships between motor speed, CMR, and backward masking tasks. Consequently, motor speed is an important construct to measure in studies assessing any influence of auditory processing in reading ability. A failure to control for motor speed in such studies may lead to spurious results based on the findings of the present research.

NVIQ correlated positively with several reading and language measures, including elision, blending and the phonological composite, word attack, passage comprehension, the Total Reading-Short Scale composite, the Core Language composite and several other language measures including expressive and receptive word classes and word definitions. The correlations found between NVIQ and the reading and language measures in the present study replicate previous research showing that increases in NVIQ correlate with increases in reading and language and provide further evidence of the well-established relationship that intelligence shares with reading and language (c.f. McGrew & Woodcock, 2001). Further, these findings support the need to control for this relationship in the IQ-discrepancy model of reading disability. NVIQ negatively correlated with several auditory outcome measures, including modulated masker, backward masking, and backward masking, notched-noise thresholds, suggesting that participants with higher NVIQ scores had lower thresholds on these masking tasks. This finding has occurred in previous research (Zettler et al., in press), and likely reflects the complexity and centrally-mediated nature of the tasks. Although the backward masking, notched-noise condition is believed to be more peripherally-based than the bandpass condition, many of the participants did not show an improvement in the notched-noise condition relative to the bandpass condition. This result may be the product of the formation of two maskers in multiple frequency regions as a consequence of the addition of the spectral notch, and therefore many participants may have experienced informational masking, a condition brought about when auditory stimuli in varying frequency regions masks the signal causing an increase in thresholds. Consequently, if this were the case then a relatively more central component would be introduced to the notched-noise task.

As expected, the reading measures from the WRMT-R/NU (word identification, word attack, and passage comprehension, in addition to the Basic Skills and Short Scale composites that are comprised of these constructs) all correlated significantly with one another, emphasizing the element of phonological awareness common to each of these measures. Additionally, word identification and word attack, along with the Basic Skills composite, correlated with RAN for letters and numbers. Several significant correlations emerged between the reading measures and the auditory measures including the CMR reference condition correlating with passage comprehension, the modulated masker condition correlating with all reading measures, backward masking correlating with all reading measures with the exception of word identification, and the backward masking, notched-noise condition correlating with all reading measures.

Word identification correlated with TOJ, yet no other reading or language measure correlated with TOJ. TOJ is a task that often has been measured in individuals with language and/or reading disorders, and unexpectedly showed little relationship with any of the reading or language variables in the present study. This finding is indicative of the tenuous relationship that TOJ tasks often share with reading. Although some research (e.g., Tallal, 1980) supports a strong relationship, results of other studies often have been unable to replicate these findings (Mody, Studdert-Kennedy, & Brady, 1997). The difficulty may stem in part from the aforementioned disagreements on what constitutes auditory temporal processing and by extension, judgments of temporal order, but the results of the present study indicate further that sampling issues may be responsible for the failure to replicate results as well. In addition, the finding that backward masking did not correlate with word identification, but TOJ threshold did suggests that unique sub-processes may underlie each of these auditory abilities.

Elision correlated significantly with the modulated masker condition and backward masking. These results are consistent with some previous research in studies of children with reading disabilities (Montgomery et al., 2005), and inconsistent with others (Zettler et al., in press), again stressing that explicitly defining sample characteristics is essential in explaining results with auditory and reading measures. Montgomery (unpublished dissertation, 2002) indicated that when five participants with NVIQ more than 2 SD greater than the mean were included in the analyses, backward masking thresholds were predicted significantly by reading disability status. However, when the data for those five participants were excluded from the analyses, this relationship was no longer statistically significant (Montgomery, unpublished dissertation, 2002). Given the strong correlation that elision has with other reading measures, and the finding that a correlation between elision and NVIQ was highly significant in the present study, it is likely that individuals with higher NVIQ scores may be the driving force behind the relationships found between auditory measures and reading measures in some studies. This explanation, also stated by Montgomery (unpublished dissertation, 2002), is supported further by the fact that both groups (participants with RD, control participants) were well-matched in terms of NVIQ in the Zettler et al. study (in press), making it more likely that a third variable, in this case NVIQ, is responsible for the relationship (or lack thereof in Zettler et al., in press) between elision and backward masking. Thus, the findings of the present study provide an empirical explanation for some of the variability found across studies measuring reading and auditory processing.

Numerous language measures correlated significantly with one another, signifying the interdependence of both the expressive and receptive components of language processing. Reference and modulated masker thresholds correlated significantly with the Core Language composite, as did both backward masking tasks, suggesting that higher language scores relate to lower thresholds on these measures, and implying a common underlying element among these abilities. Menell et al. (1999) indicate that individuals with dyslexia exhibit a reduced sensitivity to AM; consequently it is likely that AM is the timing element that is driving the correlations between the modulated masker condition and the reading and language variables. The presence of backward masking and language correlations in an unimpaired adult sample is consistent with previous research conducted with children who have both language and auditory impairments (Wright et al., 1997). These findings suggest that backward masking in particular is a task that, due to its relatively consistent relationships with both language and reading, may be a fruitful task to continue to explore in samples of individuals with language and reading impairments. Neither CMR nor the localization task showed significant correlations with any of the reading or language measures.

Reference condition thresholds were positively correlated with CMR, whereas modulated masker thresholds were negatively correlated with CMR, suggesting that participants with higher reference thresholds and lower modulated masker thresholds had greater CMR. This is the expected pattern if any CMR is measured, and confirms that the participants in the present study evidenced a release from masking. Additionally, modulated masker thresholds were correlated positively with backward masking and backward masking, notched-noise thresholds indicating that participants with high modulated masker thresholds had high backward masking and backward masking, notched-noise thresholds. It is notable that these three tasks are correlated with one another as well as being the only tasks that displayed relationships with any of the predictor variables. It is possible that these correlations reflect an underlying set of commonalities across these three measures, including timing across multiple perceptual, phonological, and motor domains of processing that may not extend to the other tasks given in this study. Further research is necessary to lend support to this assertion.

The results of this research indicate that perceptual and motor systems influence one another and are not independent. Although the common element across these systems was timing, it is clear from the results of the present study that general processing speed cannot account for all of the results, as naming speed failed to account for auditory thresholds across any of the tasks. Although both RAN and the CMR task are hypothesized to be controlled by a form of processing speed or efficiency, the processing efficiency that underlies RAN does not appear to be related to the processing efficiency that underlies CMR. Furthermore, there appears to be a complex relationship among these systems to the extent that not all of the auditory tasks were predicted by, or correlated with, the motor speed measures. Whereas the CMR conditions and backward masking conditions were predicted by motor speed, perception of the precedence effect and TOJ thresholds were not. These findings are consistent with previous research suggesting that relationships among auditory processing and reading are auditory task-specific (Amitay et al., 2002), and extend that theory to auditory and motor processing. Future research should explore the extent to which different measures of auditory temporal processing can be predicted by various language and reading measures, as it is evident that the relationships between these measures may change based on the tasks given.

The finding that TOJ was not predicted by either RAN or motor speed may indicate that the TOJ task needs to be more complex to display any relationship with RAN and motor speed.

Wolff (2002) indicated that adolescents with dyslexia performed consistently with control participants on a motor speech repetition task in which participants were asked to repeat the CV /pa/, stressing one syllable relative to the rest, in two-syllable strings. However, in the three-, or four-syllable strings, the participants with dyslexia had marked difficulty relative to the control participants, stressing the incorrect syllable in the pattern. Similar results were found by Nicolson and Fawcett (1994), who showed that participants with dyslexia performed consistently with control participants on a reaction time measure of motor speed for a simple task, but that the participants with dyslexia showed impairments as the task increased in complexity. Although the present sample was concerned with the performance of typical adults, these results suggest that task complexity may be an important variable to consider, and with regard to TOJ tasks, the two-element TOJ task presented in the present study may have been too simple to show a relationship with RAN or motor speed.

The relationships found among several of the auditory variables that require the intact perception of timing plus their subsequent links to reading and language measures lend partial support to the theory, espoused by Klein (2002) and Tallal (1980), suggesting that an auditory temporal processing deficit may be responsible for the development of RD. If the deficit is a deficit in auditory temporal processing, it follows that any processing of auditory temporal information should be disrupted. Although the results of the present study suggest that several auditory variables share similar underlying timing components that may relate to the processes of language and reading, it is also the case that not all timing is equivalent. That is, although each of the auditory measures assessed in the present study contains a timing component that must be processed effectively to successfully complete the task (with the backward masking, notched-noise task relying on spectral information being the sole exception), not all of these measures correlated with one another and not all of them correlated with language or reading measures. Thus, whereas multiple measures do appear to share a common timing element, the finding that they are not all sharing the same element argues against a purely timing-based component as a connection between auditory processing and language and reading ability.

Wolf and Bowers' (1999) hypothesis concerning as RAN being a part of a general processing speed deficit that ultimately impacts comprehension was not supported, as RAN did not correlate with comprehension in this sample of typical adults. It is possible that an impaired sample would have shown this expected pattern of results. Alternatively, as RAN is usually looking adult-like after reading ability has become fluent, it may not be surprising that no relationship is found there. It is possible that RAN may show a stronger relationship with comprehension- as well as with the auditory measures- in a sample of young children who are just learning to read.

The composite measure of language ability used herein, the Core Language score, showed little variability and scores that were quite high overall, with the lowest standard score being a 98. Language is an ability that develops early in life. As such, receptive and expressive language abilities in adults may not accurately reflect relationships between these measures and auditory processing that may be present in children who are still acquiring these abilities. Indeed, the body of research composed of studies on auditory processing in children with SLI suggests that auditory processing and language development do relate to one another (Corriveau, Pasquimi, & Goswami, 2007). However, in this sample of adult listeners with a range of temporal tasks, relationships between auditory processing and individual measures of language ability were not found, with the sole exception being reference condition thresholds correlating with the word classes-expressive and word definitions measures. Alternatively, several measures of reading ability correlated with various auditory measures, which may have been drawn out of the greater amount of variability within the sample in reading ability as compared to language ability. Thus, reading and language abilities that are developing appear to show a more direct relationship with auditory processing, whereas those abilities that are no longer changing over time, such as language processing, appear less likely to show these relationships.

Results of the auditory measures are similar to those reported in other studies with adult listeners as participants. The amount of CMR varies dramatically with changes in stimulus parameters, but the range of adult CMRs reported in the literature occur between 0-16 dB (Richards, Buss, & Tian, 1997; Hall & Grose, 1990). The 9.6 dB of masking release found in the present study falls well within this range, but more specifically, the CMR measured herein is similar to the adult value of 8.4 dB reported by Veloso et al. (1990) who used stimuli that most closely approximated those used in the present study. Research conducted on backward masking using similar stimuli and methodologies to those employed herein has shown thresholds somewhat lower than those reported in the present study. Hill, Hartley, Glasberg, Moore, and Moore (2004) assessed 12 naïve adult listeners on similar masking stimuli and found thresholds just over 40 dB, within the range of those found in the present research. However, backward masking thresholds can be quite variable. Hartley, Wright, Hogan, and Moore (2000) showed backward masking thresholds that were approximately 15 dB lower than those found in the present study (33 dB and 48 dB, respectively). Whereas both prior studies tested listeners using similar stimuli, both found somewhat disparate results. This disparity may be indicative of the relatively small sample of adults tested, which may be less representative overall than the large sample employed herein. Given that larger sample sizes more accurately reflect the true nature of the general population, the data of the present study may provide a more accurate picture of young adult listeners than is found in studies with smaller samples of listeners. Finally, the results of the localization task indicate that participants' performance followed the expected pattern as performance dropped at the very short (5 ms) delays reflecting a component of the precedence known as "fusion", in which the leading and lagging sound appear to be "fused" (Litovsky et al., 1999), making identification of the leading sound ambiguous. Performance for the group rebounded slightly at the 10 ms delay as fusion broke down, and dropped again at 20 ms, as precedence broke down. Finally, as the delay between the two clicks was increased to 50 ms and beyond, judgments of temporal order became easier and performance again improved.

Although the range of CMR found herein is typical of adults in previous studies, the stimulus parameters used in the CMR task may have unduly influenced the results of the present study. Although the stimuli were developed to elicit the maximum possible CMR based on the findings of the extant literature, given the relatively close proximity of the eight flanking bands in the modulated masker condition it is possible that within-channel cues were utilized in signal detection by listeners in the present study. Additional within-channel spectral and temporal information provided by the relatively closely-spaced flanking bands may have precluded the need to depend exclusively on the across-channel information typical of CMR. These additional peripherally-based cues may have aided in signal detection, making the task easier. Further research with flanking bands placed further apart is needed to evaluate the relationship of across-channel processing to reading and language ability.

The naïveté of the participants may have affected the results as research indicates that practice influences performance on many auditory tasks. Indeed, the impact of experience has been observed for CMR (Zettler, Sevcik, & Clarkson, 2007), backward masking (Buss, Hall, Grose, & Dev, 1999), as well as localization (Wright & Zhang, 2006) and precedence effect

(Saberi & Antonio, 2003) tasks. Adult performance on identical CMR stimuli as those used herein indicated that participants evidenced a significant improvement over time with thresholds decreasing significantly over the course of three visits. Moreover, as participants became more practiced listeners, the variability in the two conditions tended to decrease. This improvement in performance observed was not equivalent across conditions; however, as reference thresholds decreased more rapidly than modulated masker thresholds, an actual decline in the amount of CMR was observed. Participants in the Zettler et al. (2007) study did not receive language or reading measures, so the possibility that the relationships among those variables and auditory processing change with experience was not evaluated. Thus, because the participants in the present study were naïve listeners, the possibility remains that the relationships among the reading, language, motor, and auditory measures may vary based on the level of practice the listeners have. Future research should explore this question using the same tasks as those employed herein, as well as utilizing additional tasks to determine whether practice affects these relationships across a greater range of abilities.

Listeners who participated in the present study volunteered for the research and had a choice among studies in which they chose to participate. Participants chose to participate based on reading a synopsis of each study, and therefore the description of the present study may have influenced the likelihood that people who were especially good at reading or language would choose to participate in the study, as those individuals who are poor readers or had poor language skills arguably would be less likely to engage in a study in which they knowingly would be asked to read or perform language tasks. As a result, the data set may have been biased toward including those individuals who were especially good at these abilities, which may have been at least partially responsible for the numerous skewed variables found in the present study.

Therefore it is difficult to determine whether the results of the present study are generalizable to those who might be less effective at language or reading ability. Future research should assess a group of individuals with a wider range of abilities to determine whether the relationships found herein would generalize to other samples where those with difficulty in reading or language are included in the sample.

Findings from this study have important clinical implications in the assessment of any auditory deficit in individuals with RD and language deficits. First, because of the interdependence of the constructs, possibly reflecting the underpinnings of a timing mechanism common to at least some auditory, reading, and language measures, the processes of naming speed and motor speed must first be parsed out to more accurately reflect the outcome. Second, the influence of NVIQ as a driving force behind many of the language and reading measures also must effectively be controlled for to show that any differences found between clinical samples and typical individuals are due to the impairment and not intelligence. These findings also have important implications for the double-deficit hypothesis of reading disability. An important next step will be to determine, in a sample of participants with reading impairments, whether the same pattern of relationships among the reading, language, motor speed, and auditory variables emerges in individuals classified according to the double-deficit model or whether a unique pattern emerges from that of the typical sample of young adults tested herein. Research then can explore whether RAN deficits found in individuals with RD and/or language impairments impact auditory thresholds in these clinical populations. Finally, findings may change based on the participants who are sampled, underscoring the importance of explicitly defining samples in research. The determination about how to treat outliers in a data set may greatly alter the findings, and should be done cautiously to minimize their effects. Methods that should regularly be employed in research with individuals with reading and language impairments include participant matching, which would help to combat the confound of intelligence and ensure that a control sample would not be higher on this measure, thereby making it less likely that any significant results found across groups would be spurious. In addition, sampling some profiles of participants against other profiles may be an informative way to understand reading and language, particularly as knowledge of the subgroups of reading disabilities increases.

In addition to sampling issues in language and reading research, future research must explore the physiological basis of these auditory measures. The finding that not all of the auditory measures showed the same relationships with the reading and language measures indicates that different auditory tasks are mediated by different nuclei in the auditory pathway. Given that the findings of this study show that at least some of the perceptual, phonological, and motor processes are not independent but are interlinked, there are an enormous number of interactions that may explain poor performance on auditory measures by individuals with language or reading impairments. Although much behavioral data now exists on many of these auditory processes, relatively little is known about the physiological origins of these abilities. To begin to narrow the scope of explaining these relationships, it is imperative that research be directed to exploring the locus of these auditory processes. Early research indicates multiple pre-cortical areas in the auditory pathway as early as the level of the brainstem that may underlie the different tasks utilized in this study. For example, Pressnitzer, Meddis, Delahaye, and Winter (2001) found that neurons in the ventral cochlear nucleus, an important pathway in the preservation of the timing and location of sounds, respond to CMR stimuli in the anesthetized guinea pig, with the cells showing a release from masking and an early indication of responding to across-channel stimuli. Likewise, Johnson, Nicol, Zecker, and Kraus (2007) explored correlations between backward masking stimuli and consonant-vowel ("/da/") speech stimuli in the human brainstem by comparing the evoked potentials to cortical responses in children with and without learning problems. Their findings indicate a reduced responsiveness of the brainstem in response to backward masking stimuli in a subset of individuals with learning problems, a result that could, as the authors suggest, lead to a physiological explanation for subgroups of children with learning impairments performing poorly on such non-speech auditory measures. Finally, data from anesthetized cats indicates that the precedence effect has neural correlates in the auditory pathway as early as the inferior colliculus (Litovsky & Delgutte, 2002).

It is also necessary to continue the search for a rate deficit in the language and reading domain. The necessity of being able to pinpoint the locus of any rate deficit in individuals with reading impairments has been advocated by others (Wolf & Bowers, 1999), and is producing some promising lines of research indicating that regions in the thalamus and cerebellum could underlie rate and timing deficits found in language and reading problems (Galaburda, Menard, & Rosen, 1994; Nicolson & Fawcett, 1999). Such findings also could explain auditory temporal processing deficits, particularly if the neurophysiological findings between language and reading rate deficits and auditory temporal processes converge on a location shown to be common to both, such as rate deficits in the thalamus may indicate. Given that a disruption in the pre-thalamic pathways of the auditory system would disrupt processing in the thalamus in turn, the thalamus may be the most likely point of convergence for rate and timing deficits across modalities. Consequently, the further development of these lines of neurophysiological research represent an essential next step in understanding the contribution of any auditory temporal processing deficit to reading or language impairment. Once that is better understood, timing relations between auditory, reading, language, and motor measures may be easier to explicate as the underlying pathways between these measures become more readily apparent.

Chapter 5: References

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

Alcock, K., Passingham, R., Watkins, K., & Vargha-Khadem, F. (2000). Pitch and timing abilities in inherited speech and language impairment. *Brain and Language, 75*(1), 34-46.

Amitay, S., Ahissar, M., & Nelken, I. (2002). Auditory processing deficits in reading disabled adults. *Journal of the Association for Research in Otolaryngology, 3*, 302-320.

Booth, J. R., Perfetti, C. A., MacWhinney, B., & Hunt, S. B. (2000). The association of rapid temporal perception with orthographic and phonological processing in children and adults with reading impairment. *Scientific Studies of Reading, 4*(2), 101-132.

Breznitz, Z. (2003). Speed of orthographic and phonological processing as factors in dyslexia: Electrophysiological evidence. *Genetic, Social, and General Psychology Monographs, 129*(2), 183-206.

Breier, J., Gray, L., Fletcher, J., Foorman, B., & Klaas, P. (2002). Perception of speech and non-speech stimuli by children with and without reading disability and attention-deficit, hyperactivity disorder. *Journal of Experimental Child Psychology, 82*(3), 226-250.

Bruck, M. (1992). Persistence of dyslexics' phonological deficits. *Developmental Psychology, 28*(5), 874-886.

Buss, E., Hall, J., Grose, J, & Dev, M. (1999). Development of adult-like performance in backward, simultaneous, and forward masking. *Journal of Speech, Language, and Hearing Research, 42*, 844-849.

Catts, H. (1995). Early language impairments and developmental dyslexia. *Dyslexia, 1*(1), 51-53.

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

Cirino, P., Israelian, M., & Morris, R. (2005). Evaluation of the double-deficit hypothesis in college students referred for learning difficulties. *Journal of Learning Disabilities, 38*(1), 29-44.

Cohen, M., & Schubert, E. (1987). Influence of place synchrony on detection of a sinusoid. *Journal of the Acoustical Society of America, 81*(2), 452-458.

Cooper, D., Roth, F., Speece, D., & Schatschneider, C. (2002). The contribution of oral language skills to the development of phonological awareness. *Applied Psycholinguistics, 23*(3), 399-416.

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research, 50,* 647-666.

Denckla, M., & Rudel, R. (1976). Rapid automatized naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*, 471-479.

Eden, G., VanMeter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature, 382*(6586), 66-69.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin and Review, 2*(4), 460-493.

Galaburda, A., Menard, M., & Rosen, G. (1994). Evidence for aberrant auditory anatomy in developmental dyslexia. *Proceedings of the National Academy of Sciences, 91*, 8010-8013.

Green, D. (1993). Maximum likelihood method for estimating thresholds in a yes-no task. *Journal of the Acoustical Society of America, 93*(4), 2096-2105.

Griffiths,Y., Hill, N., Bailey, P., & Snowling, M. (2003). Auditory temporal order discrimination and backward recognition masking in adults with dyslexia. *Journal of Speech, Language, and Hearing Research, 46*(6), 1352-1366.

Gu, X., & Green, D. (1994). Further studies of a maximum-likelihood yes-no procedure. *Journal of the Acoustical Society of America, 96*(1), 93-101.

Hall, J., & Grose, J. (1990). Comodulation masking release and auditory grouping. *Journal of the Acoustical Society of America, 88*(1), 119-125.

Hall, J., Grose, J., & Dev, M. (1997). Auditory development in complex tasks of comodulation masking release. *Journal of Speech, Language, and Hearing Research, 40,* 946-954.

Hall, J. W., Haggard, M. P., & Fernandez, M. A. (1984). Detection in noise by spectro-temporal pattern analysis. *Journal of the Acoustical Society of America, 76*(1), 50-56.

Hartley, D., Wright, B., Hogan, S., & Moore, D. (2000). Age-related improvements in auditory backward and simultaneous masking in 6- to 10-year-old children. *Journal of Speech, Language, and Hearing Research, 43*(6), 1402-1414.

Hill, E. (2001). Non-specific nature of specific language impairment: A review of the literature with regard to concomitant motor impairments. *International Journal of Language and Communication Disorders, 36*(2), 149-171.

Hill, P., Hartley, D., Glasberg, B., Moore, B., & Moore, D. (2004). Auditory processing efficiency and temporal resolution in children and adults. *Journal of Speech, Language, and Hearing Research, 47,* 1022-1029.

Johnson, K., Nicol, T., Zecker, S., & Kraus, N. (2007). Auditory brainstem correlates of perceptual timing deficits. *Journal of Cognitive Neuroscience, 19*(3), 376-385.

Katz, W., Curtis, S., & Tallal, P. (1992). Rapid automatized naming and gesture by normal and language-impaired children. *Brain and Language, 43*(4), 623-641.

Katzir, T., Kim, Y., Wolf, M., O'Brien, B., Kennedy, B., Lovett, M., & Morris, R. (2006). Reading fluency: The whole is more than the parts. *Annals of Dyslexia, 56*(1), 51-82.

Kaufman, A.S., & Kaufman, N.L. (1990). *Kaufman Brief Intelligence Test.* Circle Pines, MN: American Guidance Service.

Keith, R. (1999). Clinical issues in central auditory processing disorder. *Language, Speech, and Hearing Services in Schools, 30*(4), 339-344.

Klein, R. (2002). Observations on the temporal correlates of reading failure. *Reading and Writing: An Interdisciplinary Journal, 15*, 207-232.

Lai, C., Fisher, S., Hurst, J., Vargha-Khadem, F., & Monaco, A. (2001). A forkhead-domain gene is mutated in a severe speech and language disorder. *Nature, 413*(6855), 519-523.

Liberman, A.M., Cooper, F.S., Shankweiler, D.P., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review, 74*(6), 431-461.

Liberman, I., & Shankweiler, D. (1985). Phonology and the problems of learning to read and write. *Remedial and Special Education, 6*(6), 8-17.

Litovsky, R., & Delgutte, B. (2002). Neural correlates of the precedence effect: Effect of localization cues. *Journal of Neurophysiology, 87,* 976-994.

Litovsky, R.Y., Colburn, H.S., Yost, W.A., & Guzman, S.J. (1999). The precedence effect. *Journal of the Acoustical Society of America*, *106*, 1633-1654.

Lyon, G.R. (1994). *Frames of reference for the assessment of learning disabilities: New views on measurement issues.* Baltimore: Paul H. Brookes.

Lyon, G., Fletcher, J., & Barnes, M. (2003). Learning disabilities. In E. Mash & R. Barkley (Eds.), *Child Psychopathology* (2nd ed., pp. 390-435). New York: Guilford Press.

Maasen, B., Groenen, P., & Crul, T. (2003). Auditory and phonetic perception of vowels in children with apraxic speech disorders. *Clinical Linguistics and Phonetics, 17*(6), 447-467.

Mather, N., & Woodcock, R.W. (2001). *Examiner's manual. Woodcock-Johnson III tests of achievement.* Itasca, Ill.: Riverside Publishing.

McAnally, K., Castles, A., & Bannister, S. (2004). Auditory temporal pattern discrimination and reading ability. *Journal of Speech, Language, and Hearing Research, 47*(6), 1237-1243.

McArthur, G., & Bishop, D. (2004). Which people with specific language impairment have auditory processing deficits? *Cognitive Neuropsychology, 21*(1), 79-94.

McCormick, M. (2000). Dyslexia and developmental verbal dyspraxia. *Dyslexia, 6*, 202-214.

McGrew, K.S., & Woodcock, K.W. (2001). *Technical manual. Woodcock-Johnson III tests of achievement.* Itasca, Ill: Riverside Publishing.

Menell, P., McAnally, K., & Stein, J. (1999). Psychophysical sensitivity and physiological response to amplitude modulation in adult dyslexic listeners. *Journal of Speech, Language, and Hearing Research, 42*, 797-803.

Miller, C., Miller, S., Bloom, J., Jones, L., Lindstrom, W., Craggs, J., et al. (2006). Testing the double-deficit hypothesis in an adult sample. *Annals of Dyslexia, 56*(1), 83-102.

Moats, L.C., & Lyon, G.R. (1993). Learning disabilities in the United States: Advocacy, science, and the future of the field. *Journal of Learning Disabilities, 26*(5), 282-294.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology, 64,* 199-231.

Montgomery, C. (2002). Auditory temporal processing in children with reading disabilities: A dissertation. Unpublished doctoral dissertation, Georgia State University, Atlanta.

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

Moore, B.C.J. (1997). *An introduction to the psychology of hearing.* London: Academic Press.

Morris, R., Steubing, K., Fletcher, J., Shaywitz, S., Lyon, G., Shankweiler, et al. (1998). Subtypes of reading disability: Variability around a phonological core. *Journal of Educational Psychology, 90*(3), 347-373.

Nicolson, R., & Fawcett, A. (1994). Reaction times in dyslexia. *The Quarterly Journal of Experimental Psychology: A Human Experimental Psychology, 47A*(1), 29-48.

Nicolson, R., & Fawcett, A. (1999). Developmental dyslexia: The role of the cerebellum. *Dyslexia 5,* 155-177.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language, and Hearing Research, 42,* 925-942.

Pressnitzer, D., Meddis, R., Delahaye, R., and Winter, I. (2001). Physiological correlates of comodulation masking release in the mammalian ventral cochlear nucleus. *The Journal of Neuroscience, 21*(16), 6377-6386.

Richards, V., Buss, E., & Tian, L. (1997). Effects of modulator phase for comodulation masking release and modulation detection interference. *Journal of the Acoustical Society of America, 82,* 165-178.

Robertson, E., Joanisse, M., Desroches, A., Ng, S., & Terry, A. (2005, April). *Do children with dyslexia also have specific language impairment?* Poster presented at the Biennial Meeting of the Society for Research in Child Development, Atlanta, Georgia.

Rosen, S., & Manganari, E. (2001). Is there a relationship between speech and non-speech auditory processing in children with dyslexia? *Journal of Speech, Language, and Hearing Research, 44*, 720-736.

Ruff, R., & Parker, S. (1993). Gender- and age-specific changes in motor speed and hand-eye coordination in adults: Normative values for the Finger-Tapping and Grooved-Pegboard tests. *Perceptual and Motor Skills, 76*(3, Pt 2) 1219-1230.

Rutter, M., & Yule, W. (1975). The concept of specific reading retardation. *Journal of Child Psychology and Psychiatry, 16*(3), 181-197.

Saberi, K., & Antonio, J. (2003). Precedence-effect thresholds for a population of untrained listeners as a function of stimulus intensity and interclick interval. *Journal of the Acoustical Society of America, 114*(1), 420-429.

Schooneveldt, G., & Moore, B. (1989). Comodulation masking release (CMR) as a function of masker bandwidth, modulator bandwidth, and signal duration. *Journal of the Acoustical Society of America, 85*(1), 273-281.

Semel, E., Wiig, E., & Secord, W. (1987). *Clinical evaluation of language fundamentals-revised.* San Antonio, TX: The Psychological Association.

Stanovich, K. (1988). Explaining the difference between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. *Journal of Learning Disabilities, 21*(10), 590-604.

Studdert-Kennedy, M. & Mody, M. (1995). Auditory temporal perception deficits in the reading-impaired: A critical review of the evidence. *Psychonomic Bulletin and Review, 2*(4), 460-493.

Tabachnick, B., & Fiddell, L. (1989). *Using multivariate statistics* (2nd ed). New York: Harper and Row.

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

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia, 11*(4), 389-398.

Vellutino, F., Fletcher, J., Snowling, M., & Scanlon, D. (2004) Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*(1), 2-40.

Veloso, K., Hall, J., & Grose, J. (1990). Frequency selectivity and comodulation masking release in adults and in 6-year-old children. *Journal of Speech and Hearing Research, 33,* 96-102.

Visto, J., Cranford, J., & Scudder, R. (1996). Dynamic temporal processing of nonspeech acoustic information by children with specific language impairment. *Journal of Speech and Hearing Research, 39,* 510-517.

Waber, D., Forbes, P., Wolff, P., & Weiler, M. (2004). Neurodevelopmental characteristics of children with learning impairments classified according to the double-deficit hypothesis. *Journal of Learning Disabilities, 37*(5), 451-461.

Waber, D., Weiler, M., Bellinger, D., Marcus, D., Forbes, P., Wypij, D., et al. (2000). Diminished motor timing control in children referred for diagnosis of learning problems. *Developmental Neuropsychology, 17*(2), 181-197.

Waber, D., Wolff, P., Forbes, P., & Weiler, M. (2000). Rapid automatized naming in children referred for evaluation of heterogeneous learning problems: How specific are naming speed deficits to reading disability? *Child Neuropsychology, 6*(4), 251-261.

Wagner, R., & Torgesen, J. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*(2), 192-212.

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1999). *Comprehensive test of phonological processing.* Austin, TX: Pro-Ed.

Watkins, K., Dronkers, N., & Vargha-Khadem, F. (2002). Behavioural analysis of an inherited speech and language disorder: Comparison with acquired aphasia. *Brain: A Journal of Neurology, 125*(3), 452-464.

Wechsler, D. (1974). *Wechsler intelligence scale for children- revised.* San Antonio, TX: The Psychological Corporation.

Wechsler, D. (1991). *Wechsler intelligence scale for children* (3rd ed). San Antonio: The Psychological Corporation.

Wechsler, D. (1997). *Wechsler adult intelligence scale* (3rd ed.). San Antonio, TX: The Psychological Corporation.

Wechsler, D. (1999). *Wechsler abbreviated intelligence scale*. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2003). *Wechsler intelligence scale for children* (4th ed). San Antonio, TX: The Psychological Corporation.

Wiederholt, J., & Bryant, B. (2001). *Gray oral reading tests* (4th ed). Austin, TX: Pro Ed.

Wolf, M., Bally, H. & Morris, R. (1986). Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired readers. *Child Development, 57*(4), 988-1000.

Wolf, M., & Bowers, (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*(3), 415-438.

Wolf, M., Goldberg O'Rourke, Gidney, C., Lovett, M., Cirino, P., & Morris, R. (2002). The second deficit: An investigation of the independence of phonological and naming speed deficits in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal, 15*(1-2), 43-72.

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

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

Woodcock, R. (1998). *Woodcock reading mastery test-revised, normative update*. Circle Pines, MN.: American Guidance Services.

Woodcock, R., & Johnson, M. (1977). *Woodcock-Johnson psychoeducational test battery.* Boston: Teaching Resources.

Woodcock, R.W., McGrew, K.S., & Mather, N. (2001). *Woodcock-Johnson III tests of achievement.* Itasca, Ill.: Riverside Publishing.

Wright, B.A., Lombardino, L.J., King, W.M., Puranik, C.S., Leonard, C.M., & Merzenich, M.M. (1997). Deficits in auditory temporal and spectral resolution in language-impaired children. *Nature, 387*, 176-178.

Wright, B.A., & Reid, M. (2002). Excessive auditory masking in children with language or listening impairments interpreted as a developmental delay. *Abstracts of the Twenty-fifth Midwinter Research Meeting of the Association for Research in Otolaryngology, 25,* 74.

Wright, B., & Zhang, Y. (2006). A review of learning with normal and altered sound-stimulus cues in human adults. *International Journal of Audiology, 45* (Supplement 1), S92-S98.

Zettler, C. (2004). Comodulation masking release in children with reading disabilities: A thesis. Unpublished Master's thesis, Georgia State University, Atlanta, Georgia.

Zettler, C., Sevcik, R., & Clarkson, M. (manuscript in preparation, 2007). Practice effects in comodulation masking release.

Zettler, C., Sevcik, R., Morris, R., & Clarkson, M. (in press). The development of comodulation masking release and the influence of reading status. *Journal of Speech, Language, and Hearing Research.*