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An Investigation of Temporal Resolution Abilities in School-Aged Children With and Without Dyslexia

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AN INVESTIGATION OF TEMPORAL RESOLUTION ABILITIES IN SCHOOL-AGED CHILDREN WITH AND WITHOUT DYSLEXIA

A Dissertation Presented

By

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DEDICATION

This work is dedicated to my mother who was always my role model and to my father who was the most loving and kind person I have ever known. Next, to Oliver who was always there. Finally, to my husband and daughter who mean everything to me and whose love and friendship helped me stay focused on the project and gave me encouragement to continue to its end.

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ABSTRACT

AN INVESTIGATION OF TEMPORAL RESOLUTION ABILITIES IN SCHOOL-AGED CHILDREN WITH AND WITHOUT DYSLEXIA

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Dyslexia is a clinical diagnosis often associated with phonological processing deficits. There are, however, other areas of concern, such as the presence of auditory temporal processing (ATP) disorders. One method of investigating ATP is the gap detection (GD) paradigm. This study investigated GD performance using the Gaps-in-Noise© (GIN) test in three groups of 30 children, aged 8 to 9 years. GD thresholds and gap identification scores (%) were determined for each participant. The three groups of participants included (Group I) children with dyslexia and phonological deficits, (Group II) children with dyslexia and no significant phonological deficits, and (Group III) normal reading peers. Repeated-measures ANOVA showed that GD thresholds for the three groups were significantly different. Group I showed longer GD thresholds (RE, 8.5 msec; LE, 8 msec), than did Group II (4.9 msec for both ears) or Group III (RE, 4.2 msec; LE, 4.3 msec). Close inspection of the threshold values for the three groups revealed that the thresholds for Group II overlapped substantially with those of Group III, but not with those of Group I. Similar trends were also noted for the gap identification analysis.

From a clinical perspective, the majority of participants in Group II and all participants in Group III performed within normal limits on both measures (i.e., thresholds and identifications), while performance of participants in Group I fell below established norms on these measures. Finally, additional analyses revealed that ATP was highly correlated with phonological processing measures indicating a relationship between the presence of phonological deficits and ATP deficits. This study confirmed that ATP deficit is a factor to be considered in dyslexia and suggested that the GIN© test is a promising clinical tool that should be incorporated in the evaluation procedures for children with reading difficulties.

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INTRODUCTION

Reading disability or dyslexia is a heterogeneous neurological syndrome characterized by an unexpected difficulty in normal reading acquisition in children and adults who otherwise possess the intelligence and motivation considered necessary for accurate and fluent reading (Shaywitz & Shaywitz, 2005). Lyon, Shaywitz, and Shaywitz (2003) defined reading disability as “a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction.” (Lyon et al., 2003, p.2).

Recent epidemiologic data indicate that dyslexia fits a dimensional model (Shaywitz & Shaywitz, 2005). In other words, within the population, reading ability and reading disability occur along a continuum, with reading disability representing the lower end of a normal distribution of reading ability (Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Talcott, Witton, McClean, Hansen, Rees, Green, & Stein, 2000).

Dyslexia is perhaps the most common and the most carefully studied neurobehavioral disorder affecting children, with reported prevalence rates ranging from 5% to 17% (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Lyon, 1995; Shaywitz, 1998; Giraud, Démonet, Habib, Marquis, Chauvel, & Liégeois-Chauvel, 2005). Moreover, it is a neurobiological condition that reportedly affects approximately 80% of all individuals identified as learning disabled (Bell, McCallun, & Cox, 2003; Shaywitz, Gruen, & Shaywitz, 2007). Longitudinal studies, both prospective (Shaywitz, Fletcher, & Holahan, 1995; Francis, Shaywitz, & Stuebing, 1996) and retrospective (Scarborough, 1990; Bruck, 1992), indicate that dyslexia is a persistent, chronic condition; i.e., it does not represent a transient developmental lag as is the case with some other childhood disorders. As a result, individuals with reading disability are likely to struggle throughout their lifetime with their reading difficulties, and the impact of poor reading skills on general health and well being can be extensive. For example, reading disability has been associated with both poor health and behavior problems (Weiss, 1997; McGee, Share, Moffitt, Williams, & Silva, 1998). Given that reading disability adversely affects the lives of so many, it is important to clearly understand the causes and development of this disability. Gaining such an understanding will allow for more effective methods of diagnosing and remediating the disability, and may eventually lead to the development of efficacious preventative interventions.

Etiological Bases of Reading Disability

A great deal of disagreement exists among researchers concerning the etiology of dyslexia or reading disability. The predominant view is that phonological processing deficits are the basis of reading disorders (Bradley & Bryant, 1978; Shaywitz, 1998). Some researchers, however, have provided evidence that a magnocellular system deficit in visual processing exists in at least some individuals with reading disability (Williams, Brannan, & Lartigue, 1987). Yet, other researchers have asserted that an auditory temporal processing deficit is associated with reading disability (Tallal, 1984; Farmer & Klein, 1995).

Indeed, the majority of individuals with dyslexia suffer from poor phonological processing skills that result in difficulties in perceiving and decoding words. In addition, they commonly experience challenges in manipulating speech sounds (Snowling, 2000). These phonologically-based impairments are believed to be directly linked to reading disability because skilled decoding of the alphabetical script requires the ability to relate visual symbols to speech sounds (Cohen-Mimran, 2006). Researchers who approach reading disability from the phonological processing perspective assert that the disability is fundamentally a linguistic problem that is not related to either visual or auditory perceptual difficulties (Bradley & Bryant, 1978; Siegel, 1993; Snowling, Nation, Moxham, Gallagher, & Frith, 1997; Shaywitz, 1998).

On the other hand, a large number of researchers have shown that many individuals with reading disability and comorbid phonological deficits also show visual and/or auditory temporal processing difficulties (Lovegrove, Bowling & Babcock, 1980; Tallal & Stark, 1982; Martin & Lovegrove, 1987; Edwards & Ball, 1995; Goswami, 2000; McArthur & Bishop, 2001; Boets, Wouters, van Wieringen, De Smedt, & Ghesquière, 2008). Therefore, it is possible that some individuals with reading disability have comorbid visual and auditory temporal problems in addition to their phonological processing deficits. For example, Edwards (2000) found that although phonological processing measures were stronger predictors of reading performance than either visual or auditory temporal processing measures, a group of adults with persistent reading disability (i.e., those with persistent phonological awareness deficits) and some individuals with compensated reading disability clearly showed auditory temporal processing deficits. The author concluded that individuals with reading disability have difficulties on tasks that require phonological and/or auditory temporal processing skills and that better auditory temporal and phonological processing skills are associated with better reading ability.

In order to examine whether the main cause of literacy-impairment was at the phonological level or at a more basic sensory level, Boets, Wouters, van Wieringen, and Ghesquière (2007) assessed phonological ability, speech perception, and low-level auditory processing skills in a group of 62 children who were followed from one year before the onset of formal reading instruction until one year into reading instruction. Based on family risk status for dyslexia and first grade literacy achievement the children were categorized into three groups (low family risk and normal literacy skills, high family risk and impaired literacy skills, and high family risk and age-appropriate literacy achievement) and their pre-school data were retrospectively reanalyzed. Overall, children showing both increased family risk and literacy-impairment at the end of first grade presented significant pre-school deficits in phonological awareness, rapid automatized naming, speech perception, and auditory frequency modulation (FM) detection. The authors argued that although the concurrent presence of these deficits in this group before receiving any formal reading instruction might suggest a causal relation with problematic literacy development, a closer inspection of the individual data indicated that the core of the literacy problem was situated at the level of higher-order phonological processing. They based this claim on three observations: first, not all literacy-impaired subjects demonstrated auditory and/or speech perception deficits; second, some normal reading subjects also showed auditory and/or speech perception problems, and finally, a consistent pattern of deficiencies across auditory processing, speech perception, and phonological abilities was not observed. On the other hand, the authors emphasized that even though auditory and/or speech perception deficits were not a necessary condition for the development of reading and spelling problems, their presence might have aggravated the phonological and literacy impairments.

A number of additional studies have implicated the presence of auditory temporal processing deficits in individuals diagnosed with dyslexia. Habib, Espesser, Rey, Giraud, Bruas, and Gres (1999) found that phonological training with individuals with dyslexia was more effective when the speech stimuli were modified temporally (e.g., modification of the acoustic characteristics of the speech stimuli, such as consonant and vowel frequency spectrum, duration, etc.). Kujala, Karma, Ceponiene, Belitz, Turkkila, Tervaniemi, and Näätänen (2001) found that children with dyslexia who had been enrolled in an audiovisual training program using non-linguistic materials showed (1) plastic changes in their auditory cortices, as indexed by enhanced electrophysiological Mismatch Negativity (MMN) measures, (2) faster reaction times to subtle changes in the sound stimuli, and (3) significant improvements in their reading skills when post-treatment data were compared to pre-treatment measures. The authors concluded that the fact that these training effects were obtained with non-linguistic training materials indicated that dyslexia was based, at least in part, on a more general auditory perceptual deficit.

In another investigation, children's sensitivity to both dynamic auditory and visual stimuli was found to be directly related to their literacy skills (Talcott et al., 2000). After controlling for intelligence and overall reading ability, Talcott and colleagues found that visual motion sensitivity explained independent variance in orthographic skill but not phonological ability, and that auditory sensitivity to a FM stimulus (i.e., a temporal resolution measure) co-varied with phonological skill, but not with orthographic skill.

Boets and colleagues (2008) compared the performance of 62 children with family risk for dyslexia who were part of an ongoing longitudinal research project (Boets, Wouters, van Wieringen, & Ghesquière, 2006) on dynamic auditory (FM detection) and visual processing (coherent motion detection) tasks, speech-in-noise perception, phonological ability, and orthographic ability. The relationships between each of these variables were analyzed using causal path analysis. The results suggested that dynamic auditory processing influences phonological awareness in a direct way and it is also related to speech perception, which in turn is related to phonological awareness. In addition, these researchers found that dynamic visual processing was related to orthographic skill. Based upon these findings the authors concluded that the observed sensory deficits and their relationships to higher order skills (i.e., speech perception, phonological, and/or orthographic skills) were not merely a consequence of reading failure or a variation in reading disability, indicating that these sensory deficits must be considered when assessing and treating literacy difficulties as auditory processing ability, speech perception, and phonological ability influence each other reciprocally.

In order to verify whether abnormal auditory processing in dyslexia was accompanied by abnormal anatomical variations in the auditory system, Galaburda, Menard, and Rosen (1994) measured cross-sectional neuronal areas in the medial geniculate nuclei (MGNs) of five brains from individuals with dyslexia and seven control brains. The authors found that the brains of the subjects with dyslexia showed structural asymmetries in the left and right-sided MGNs, wherein the neurons in the left MGNs were significantly smaller than those noted in the right MGNs. Importantly, smaller neurons have been shown to be slower processors (Lawson & Waddell, 1991). This observation was not consistent with the findings for the brains of the control subjects, which showed symmetrical right and left MGNs.

In an earlier study, Galaburda, Sherman, Rosen, Aboitiz, and Geschwind (1985) examined the brains of four adult males with developmental dyslexia and found neuroanatomical anomalies in the auditory regions; i.e., the post-mortem studies of these four brains revealed (1) a symmetry in the size of the planum temporale in the two hemispheres, representing a cerebromorphological deviation from the typical pattern of cerebral asymmetry observed for normal readers, and (2) developmental anomalies of the cerebral cortex (e.g., neuronal ectopias and architectonic dysplasias) affecting preferentially, but not exclusively, the perisylvian regions of the left hemisphere. The authors hypothesized that these neuroanatomical findings were causally related to dyslexia. Similar post-mortem findings (i.e., symmetry of the planum temporale and developmental anomalies) were reported in a subsequent study conducted by Humphreys, Kaufmann, and Galaburda (1990) who studied the brains of three adult females with histories of developmental dyslexia.

In a 2002 book chapter, Galaburda provided additional discussion of the potential anatomical correlates of dyslexia. In this chapter Galaburda identified the presence of both ectopias (i.e., neuronal migration anomalies in which neurons migrate to inappropriate sites within the cortex and/or the subcortical white matter) and focal mycrogyria (i.e., areas of the cortex that include four cortical layers instead of six) as two potential anatomical variations within the human brain that may be associated with dyslexia. These ectopias and mycrogyria were found to interfere with rapid auditory processing of tones and their presence in the cortex early in development was accompanied by anatomical changes close and far afield, both within and between hemispheres. For example, microgyria in the frontal cortex produced changes in neuronal sizes in the thalamus, and probably in all intervening neuronal processing stations along the central auditory nervous system. The author suggested that these changes in the thalamic and other auditory relay nuclei could specifically account for abnormalities in sound processing abilities and that anatomical variations in the frontal lobe could explain problems with phonological processing.

The foregoing studies have documented structural differences in the afferent cortical and subcortical areas of the central auditory nervous system in individuals with dyslexia. Some more recent investigations have studied the functionality of the medial olivocochlear system (MOC), an auditory efferent pathway functioning under central control, and have reported a link between the functionality of this system and dyslexia for both children and adults (Veuillet, Magnan, Ecalle, Thai-Van, & Collet, 2007; Hoen, Grataloup, Veuillet, Thai-Van, Collet, & Meunier, 2008).

Veuillet and colleagues (2007) conducted a two-experiment study involving children with and without dyslexia. Their first experiment compared the performance of children with average reading ability to that of children with dyslexia on a categorical perception task specifically designed to assess the processing of the phonemic contrast (/ba/ vs. /pa/) by varying the acoustic cue, voice onset time (VOT). In this experiment MOC functionality was investigated through the use of evoked otoacoustic emissions, an electroacoustic test that assesses the functioning of the cochlea. MOC system functionality was examined based on the differences in the response suppression effects noted between right and left ears responses during evoked otoacoustic emissions testing. Results showed an altered sensitivity to VOT differences in most of the children with dyslexia, and a definite relationship between the severity of the VOT deficits and the severity of the participants' reading difficulties. The deficits in VOT perception, which were noted among the children with dyslexia, were sometimes accompanied by MOC function abnormalities; i.e., in average-reading children, the MOC system was much more functional in the right ear than in the left ear, but predominated in the left ear in children with dyslexia. Moreover, a significant difference was observed between the two groups in the right ear, suggesting a deficit of MOC functioning in the right ear but not in the left ear in children with dyslexia.

In the second experiment, the authors investigated whether audiovisual training focusing on a voicing contrast could modify VOT sensitivity in participants with dyslexia and induce MOC plasticity. The authors found that audiovisual training significantly improved reading abilities in their subjects with dyslexia and shifted their categorical perception curves towards the average-reading children's pattern of voicing sensitivity. In half of these children, MOC functioning showed increased asymmetry in favor of the right ear following audiovisual training. The training-related improvements in reading scores were greatest in children presenting the greatest changes in MOC lateralization. The authors concluded that these findings supported their contentions that some auditory system processing mechanisms are impaired in children with dyslexia and that audiovisual training can diminish these deficits.

Hoen and colleagues (2008) extended the findings reported by Veuillet and colleagues (2007) by comparing the speech-in-speech comprehension performance of a group of control participants and a group of adults who had been diagnosed with dyslexia as children. Their results evidenced greater difficulty on the part of the adults with dyslexia in comprehending speech in noise and suggested a link between this finding and MOC functionality as assessed with evoked otoacoustic emissions. Specifically, their results showed that the MOC functionality of the participants with dyslexia lacked asymmetry while the normal readers demonstrated a functional asymmetry favoring the right ear.

In summary, the results from the studies mentioned above supported the presence of a phonological deficit in dyslexia but also provided empirical and anatomical evidence of a deficient sound-processing basis for the reading difficulties experienced by many individuals with dyslexia. This ongoing debate about the etiological basis of reading disability (i.e., phonological theory, auditory temporal processing theory, or the visual magnocellular theory) is important and necessary to guide and stimulate further research into the underlying causes and manifestations of reading disorders (Boets et al., 2007). Given what is currently known, it is unreasonable to expect that any one of the three theories mentioned above will be able to fully explain the complexity of disordered or delayed literacy development. Just as decades of research into the behavioral manifestations of reading difficulties has failed to uncover a single behavioral manifestation of dyslexia, it is unlikely that researchers will be able to identify a single cause or etiological basis for the disorder.

In this line, Pennington (2006) proposed a broader conceptual change from the single-cause model for developmental and learning disorders to a probabilistic and multifactored model. This model proposes that (1) the etiology of complex behavioral disorders is multifactorial and involves the interaction of multiple risk and protective factors, which can be either genetic or environmental; (2) these risk and protective factors alter the development of the cognitive functions that are necessary for normal development, thus producing the behavioral symptoms that define these disorders; (3) no single etiological factor is sufficient for the disorder, and in fact, it is possible that a few may be necessary; (4) comorbidity among reading disorders and other complex behavioral disorders is to be expected because of shared etiologic and cognitive risk factors; and (5) the liability distribution for a given disease or disorder is often continuous and quantitative, rather than being discrete and categorical; therefore, the threshold for having the disorder may be somewhat arbitrary. Pennington's (2006) model suggests that achieving a complete understanding of the causes and development of disorders like dyslexia would be very difficult, if not impossible, because of the multiple pathways that are or can be involved.

Subtypes of Reading Disability

Some researchers have proposed that the conflicting results of earlier studies (i.e., some showing that individuals with reading disability have language deficits, whereas others have documented visual and/or auditory perceptual deficits) reflect the fact that there are likely different subtypes of reading disability (Borsting, Ridder, Dudeck, & Kelley, 1996; Banai, Nicol, Zecker, & Kraus, 2005). Based upon this claim, reading disability would be viewed as being composed of a heterogeneous group of disorders that could be subdivided into distinct subtypes of reading disorders predicated upon the identification of common attributes. Thus, individuals with reading disability would exhibit a variety of cognitive, linguistic and/or perceptual deficits, and the types of exhibited deficits would depend upon the specific subtype of reading disability experienced.

Many different subtyping paradigms can be found in the literature. One published subtype paradigm that is often used is Boder's (1971) classification system. Boder identified three distinct patterns of reading disabilities based on the nature of the spelling errors made by individuals with reading disability. These subtypes were characterized by (1) difficulty with sound and symbol association, (2) difficulty remembering visual aspects of words, and (3) a combination of difficulties in these two areas. Some researchers, however, have reported difficulty classifying participants into these subtypes (Nockleby & Glabraith, 1984; Slaghuis, Lovegrove, & Davidson, 1993).

Castles and Coleheart (1993) suggested that at least two varieties of reading disabilities can be identified that may roughly correspond to the phonological and visual subtypes. They also found that a majority of individuals with reading disability have mixed deficits. Using this method of subtyping, however, Spinelli, Angelelli, De Luca, Di Pace, Judica, and Zoccolotti (1997) in a study involving children presenting with the characteristics of visual dyslexia (i.e., slow and laborious reading with errors in tasks which cannot be solved with a grapheme-phoneme conversion) found that visual processing was within normal limits for the majority of the individuals tested.

Other researchers have attempted to explain divergent findings within the reading disability literature by considering the various ways that researchers have defined reading disability (Stanovich, 1993). There is much debate and disagreement among researchers about how reading disability should be defined. From legal and educational perspectives, reading disability usually involves the presence of a discrepancy between reading ability and intelligence. Such discrepancy is based upon the assumption that reading disability stems from problems that are distinguishable from those which characterize other individuals with poor reading ability, such as individuals with low intellectual functioning or insufficient motivation (Stanovich, 1991). However, there is some disagreement with the use of this traditional definition of reading disability (Siegel, 1988). Siegel (1992) found evidence that individuals with low IQs and low reading scores performed similarly to individuals with reading disability on a variety of spelling, reading, and phonological processing tasks. It also has been argued that deficits in areas other than phonological processing have been found in populations with reading disability due to the fact that some researchers did not distinguish between poor readers and individuals with reading disability (Stanovich, 1993). An important question that currently remains unanswered is if reading ability and reading disability do in fact occur along a continuum as suggested by Shaywitz and colleagues (1992) and Talcott and colleagues (2000), where should the line separating normal and abnormal performance be drawn? A related question which deserves further clinical investigation is which assessment test battery or batteries would be most appropriate for the comprehensive assessment and documentation (i.e., both identification and qualification) of the cognitive, linguistic, and/or perceptual difficulties experienced by children with reading disability?

Diagnosis of Reading Disability

As stated above, research has identified a range of cognitive and academic variables that have been implicated in the identification of dyslexia. Questions remain about which variables are most critical in explaining reading abilities and disabilities and about the nature of the interrelationships among these variables. Knowledge of the relationships among various cognitive abilities and reading skill areas can provide a better understanding of the cognitive precursors of reading problems and guide the development of a more uniform assessment approach to the identification of dyslexia. Unfortunately, the diagnosis and identification of dyslexia are hampered by the lack of consensus about diagnostic labels and the specific neurobiological processes underlying dyslexia as well as by the lack of generally accepted standards or procedures for the diagnosis of this disorder. Further, the use of a variety of different diagnostic instruments for assessment purposes across clinical investigations creates problems. For example, comparisons across different standardization samples produce errors and different examiners may choose different instruments to assess the same cognitive skills and these cognitive skills are not assessed in the same manner across different tests.

Currently, dyslexia is a clinical diagnosis in which the clinician seeks to determine through history, observation, and psychometric assessment if there are unexpected difficulties in reading and associated linguistic problems at the level of phonological processing. Dyslexia is commonly distinguished from other disorders that may prominently feature reading difficulties by the unique, circumscribed nature of the phonological deficit

(Peterson, McGrath, Smith, & Pennington, 2007). Unfortunately, despite recent findings documenting the complexity of the disorder, visual and auditory temporal processing assessments are not commonly employed in the diagnosis of reading disabilities. Also, as there is no single test score that is pathognomonic of dyslexia, its diagnosis should reflect a thoughtful synthesis of all the available clinical data, as has been suggested by Shaywitz et al. (2007).

A detailed history of a child's difficulties can provide the identification of important risk factors for the presence of a reading disability. Specifically, a history of difficulty getting to the basic sounds of spoken language, of laborious and slow reading and writing, of poor spelling, or of requiring additional time to complete reading assignments or tests, may provide evidence of a deficiency in phonological processing, which is considered by many researchers as the basis of reading disability (Shaywitz et al., 2007).

In the preschool child, a history of language delay or of not attending to the sounds of words (e.g., trouble learning nursery rhymes or playing games with words that sound alike, mispronouncing words, etc.), trouble learning to recognize the letters of the alphabet, and a positive family history represent important risk factors for dyslexia (Shaywitz et al., 2007).

Grizzle (2007) suggested that for kindergarteners and first grade children who are in the process of developing decoding abilities, proficiencies in skills critical to early reading are good predictors of later reading problems. These skills include phonological awareness, working memory, serial naming, and expressive vocabulary.

Among school-aged children, Grizzle (2007) and Shaywitz and colleagues (2007) suggested that the diagnosis of dyslexia should be based on the assessment of (1) phonological abilities at the syllable and phoneme levels; (2) reading skills, including measurement of word reading, reading fluency, and reading comprehension; (3) vocabulary; (4) knowledge of letter names and sounds; and (5) listening comprehension. Although these authors suggested that the diagnosis of dyslexia should be based upon the assessment of these skill areas, they failed to define the specific criterion or criteria that must be met for the diagnosis of dyslexia (e.g., a deficit in one of these skill areas, two of these skill areas, some other combination of criteria, etc.).

Padget, Knight, and Sawyer (1996) provided a diagnostic profile of dyslexia, which delineated the specific assessment data necessary to obtain an accurate diagnosis for reading disability. This profile described the relative performance levels of various cognitive and academic components. Generally, in order to diagnose a reading disability, listening comprehension, intelligence scores (IQ), or both must be in the low-average range or higher. Reading comprehension scores must be lower than listening comprehension or IQ, with significant weaknesses noted in word recognition, spelling, and word attack (i.e., decoding of nonsense words). Also, phonological awareness skills must be well below age expectations.

Bell and colleagues (2003) criticized Padget and colleagues' (1996) model by emphasizing that their profile fails to include rapid automatized naming (RAN) as a component of the dyslexia profile. Rapid automatized naming has indeed been implicated in dyslexia and is considered an important factor in diagnosing reading problems by some researchers (Manis, Doi, & Bhadha, 2000; Wolf & Bowers, 2000; Bell et al., 2003), especially in languages with transparent phonetic structures (Henry, Ganschow, & Miles, 2000).

Also, the use of intelligence testing in the identification of reading disability as proposed by Padget and colleagues (1996) is highly controversial. A recent report from the International Dyslexia Association (2002) included conclusions that the aptitude-achievement discrepancy method of determining learning disability is neither reliable nor educationally relevant. Further, discrepant (IQ > academic achievement scores) and nondiscrepant poor readers do not differ from each other in their prognosis over time (Francis et al., 1996) or in their response to educational interventions (Stage, Abbott, & Jenkins, 2003).

Bell and colleagues (2003) proposed that the assessment of dyslexia should include measures of auditory processing (e.g., auditory synthesis, phonemic awareness, phonological skills), visual processing speed (e.g., visual discrimination, rapid automatized naming) and memory (both auditory and visual) in addition to specific measures of reading achievement. The authors found that the use of three measures contributed to the accurate prediction of reading and spelling skills of 105 elementary and middle school students.

In conclusion, the utilization of a test battery which includes both cognitive and perceptual tests should help clinicians and researchers to differentiate among various dyslexic pattern profiles, with the understanding that not all scores will be low for all students with dyslexia and that there are several clinical manifestations of the disorder that will require different remediation methods. Further, although phonological processing deficits may be at the core of the deficiency for many individuals with reading difficulties (Bradley & Bryant, 1978; Shaywitz, 1998; Peterson et al., 2007; Shaywitz et al., 2007), clinicians must be in a position to identify other sensory and/or cognitive deficits that may impact the individual's reading abilities as alternative intervention protocols may be indicated based upon the presence or absence of these perceptual or cognitive skills.

Rationale for the Present Investigation

A critical goal that should be carefully considered when working with the heterogeneous group of individuals with reading problems, especially children, is to identify not only areas of weakness but also areas of true potential so that this information can be used to help foster academic and social development. Reading and writing is a complex and multifaceted activity that involves a dynamic interplay of multiple sensory and cognitive-linguistic processes, moderated by various environmental or higher-order cognitive influences. Deficits at any level might interfere with normal literacy development. Thus, the proper and accurate classification of the deficits experienced by individuals with dyslexia represents a challenge for the researcher and/or clinician involved in the study of reading disabilities. It is already known that phonological awareness difficulties must be considered during the assessment and remediation processes of individuals with dyslexia. There are, however, other areas of concern. One of them is the presence of auditory temporal processing disorders in dyslexia. Its exact relationship to reading disabilities is yet to be determined but it is undeniable, based on the most recent research results, that auditory temporal processing must be a factor to be accounted for when studying dyslexia. The present investigation examined the presence or absence of auditory temporal processing disorders in two groups of participants who have been diagnosed as dyslexic (one with obvious phonological processing deficits and a second with only mild phonological processing deficits or with no evidence of phonological awareness difficulties) and a group of typically developing readers in an effort to determine if auditory temporal processing skills covary with the phonological processing abilities of individuals in these three groups.

CHAPTER 2
REVIEW OF THE LITERATURE

Auditory Temporal Processing

The basic and clinical auditory sciences are devoting increasing effort to elucidating the temporal processes involved in auditory perception since both speech and non-speech sounds are physical events that are distributed in time (Phillips, 1999). Auditory temporal processing is defined as the perception of sound or of the alteration of sound within a restricted or defined time interval (Musiek, Shinn, Jirsa, Bamiou, Baran, & Zaidan, 2005). It can also be defined as the manner in which sequences of sounds evolve over time or as the time-related aspects of the acoustic signal (Bellis, 2003). The sound's identity and location are determined by the manner in which this evolution happens. Therefore, adequate auditory perception requires the accurate processing of the sound-time structure of an acoustic event (Musiek et al., 2005).

Auditory temporal processes are critical to a wide range of auditory and auditory-language behaviors, including rhythm perception, periodicity, pitch discrimination, duration discrimination, phoneme discrimination, segregation of auditory figure from auditory ground (i.e., listening in noise or competition), speech perception, and perception of music (Tallal, 1976; Leitner, Hammond, Springer, Ingham, Mekilo, Bodison, Aranda, & Shawaryn, 1993; Phillips, 1999, 2002; Downie, Jakobson, Frisk, & Ushycky, 2002; Rupp, Gutschalk, Hack, & Scherg, 2002). If a listener takes the time to analyze the acoustic segments of speech that individual will come to the realization that speech consists of sound elements and combinations of sound elements (linguistic events) that are temporal and sequential in nature (Pinheiro & Musiek, 1985).

Auditory temporal processing is also an ability or underlying skill that is necessary for the accurate discrimination of subtle acoustic cues, such as voicing differences, which serve as the foundation for the discrimination or differentiation of words that are highly similar in their acoustic characteristics (Phillips, 1999; Bellis, 2003). Other researchers have emphasized the role of temporal processing across a range of language processing skills, from phonemic distinctions (e.g., voice-onset time (VOT) differentiation which underlies cognate discrimination) to lexical distinctions, temporally cued prosodic distinctions, and the resolution of ambiguity (Chermak & Musiek, 1997).

Work carried out by Tallal and colleagues suggested that specific language impairment (SLI) is a consequence of poor auditory temporal processing (Tallal & Piercy, 1973, 1974, 1975; Tallal, 1976, 1980a; Tallal & Stark, 1982; Tallal, Miller, & Fitch, 1993). For example, Tallal and Piercy (1974) showed that many children with language impairments were unable to discriminate both rapidly presented auditory patterns as well as synthesized stop consonants when these stimuli were presented at short interstimulus intervals (ISIs). In a later study, these same authors demonstrated that children with language impairments were able to differentiate between consonant-vowel syllables if the initial formant transitions of the stop consonants were lengthened (Tallal & Piercy, 1975), clearly implicating an auditory basis for the speech perception difficulties of children with SLI. These findings led to the suggestion that children with language impairments suffer from a more basic auditory temporal processing deficit which interferes with the accurate perception of rapid spectral changes, particularly those provided by the fast formant transitions of stop consonants. This inability to detect formant transitions then, in turn, is believed to interfere with the ability to discriminate and categorize speech sounds (Tallal, 1980b).

Like auditory language impairments, reading and spelling difficulties were hypothesized to arise from deficits in auditory temporal processing skills. In other words, it was suggested that poor auditory temporal processing skills would interfere with the ability to discriminate many speech sounds, which in turn, would impair the development of accurate phonological processing skills, such as phonological awareness and segmentation (Tallal & Stark, 1982). Thus, without the necessary knowledge and skills required to break words into their phonological components, it is likely that children with such auditory-based deficits will not be able to accurately map speech sounds on their written symbols, which then results in an impairment in the development of normal reading and spelling skills. Although temporal processing deficits have been linked to language and reading problems (Merzenich, Jenkins, Johnston, Schreiner, Miller, & Tallal, 1996; Helenius, Uutela, & Hari, 1999; Walker, Shinn, Cranford, Givens, & Holbert, 2002; Baran, Bothfeld, & Musiek, 2004), this purported linkage remains controversial (Bishop, Carlyon, Deeks, & Bishop, 1999; Nittrouer, 1999).

Buonomano and Karmarkar (2002) argued that without an understanding of the neural mechanisms underlying auditory temporal processing, it would not be possible to understand how the brain processes complex acoustic stimuli, which are characterized by both their spatial and temporal features. There are a number of subcategorizations of auditory temporal processing skills which are used to better understand its mechanisms. These include (1) temporal integration, i.e., the ability of the auditory system to integrate information over time to enhance detection or discrimination of the stimulus; (2) temporal sequencing, i.e., the perception and/or processing of two or more auditory stimuli in terms of their order of occurrence in time; (3) temporal masking, i.e., the masking that occurs when the threshold or perception of one sound shifts due to the presence of another sound which precedes or follows it; and (4) temporal resolution, i.e., the ability of the auditory system to detect changes in a stimulus over time. Although these auditory temporal processing skills have been studied extensively in the research arena using a variety of experimental test stimuli and assessment paradigms, many of these procedures have not been effectively translated to clinical application due to the nature of the experimental tasks used (i.e., lengthy psychoacoustic procedures) and the contradictory findings that are widely reported in the literature. This latter situation most likely occurs because researchers are frequently required to develop their own assessment procedures when studying targeted populations as there is a relative paucity of clinical measures of auditory temporal processing. This in turn creates problems when comparing the results of such studies because comparisons between and across multiple and varying test procedures can produce errors and ultimately contradictory findings when these procedures are being used to assess the same underlying skill or mechanism.

Auditory Temporal Processing and Dyslexia

The auditory temporal processing deficit hypothesis in reading disabilities originated from studies on children with SLI and was then later extended to children with dyslexia (Tallal & Piercy, 1973; 1974; 1975; Tallal, 1976; Tallal, 1980a; Tallal & Stark, 1982). The empirical evidence for temporal processing deficits in individuals with reading disability was presented in Tallal's early study which used a temporal order judgment (TOJ) task to assess auditory temporal processing abilities (Tallal, 1980a). For this experimental task two complex tones with different fundamental frequencies were presented in pairs at various ISIs and the participants responded with two button presses to identify the order of the stimuli presented (i.e., low-low, low-high, high-low, or high-high). Tallal found that children with dyslexia when compared to normal readers were impaired in their ability to discriminate and sequence pairs of brief auditory stimuli with short ISIs. This led her to conclude that the auditory deficits experienced by children with dyslexia are specific to the processing of auditory stimuli that are brief in duration and that occur in rapid succession. Moreover, she found a high correlation between this basic perceptual processing of non-speech signals and the participants' phonological skills.

Following further evidence that dyslexic and SLI children had great difficulty discriminating syllables containing stop consonants, the claim of an underlying auditory temporal deficit was extended to apply to both non-linguistic as well as linguistic stimuli (Tallal & Piercy, 1973; Tallal et al., 1993). Since the discrimination of syllables critically depends on the accurate detection of the rapid frequency changes in the first milliseconds (msec) of voicing, inaccurate detection of these formant transitions would inevitably interfere with the identification of the phonological cues that are typical for spoken language (Boets et al., 2006). This hypothesis of a direct association between basic auditory processing and speech or language processing was strengthened by the results of a study by Tallal and Piercy (1975), which demonstrated that speech stimuli with lengthened transitions were discriminated with higher accuracy than the same stimuli with typical transition durations. This association generated the claim that an underlying auditory temporal problem caused the language processing deficits, which were manifested as deficient or delayed phonological processing and reading skill development. Thus, this possible causal mechanism has been put forward as a plausible explanation of the underlying deficits noted in dyslexia.

Since the formulation of this theory there have been multiple studies exploring the auditory temporal abilities of individuals with dyslexia. The results of these studies, however, have often been contradictory and have led to considerable controversy among researchers regarding the role of auditory temporal processing deficits in dyslexia. Whereas several researchers have emphasized the high incidence of auditory deficits in individuals with reading disability and suggested a causal link (Tallal, 1980b; Talcott & Witton, 2002; Goswami, 2003; King, Lombardino, Crandell, & Leonard, 2003), others have argued that these deficits cannot be considered a major factor in dyslexia because not all individuals with dyslexia display them (Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003; Rosen, 2003). These discrepant findings are likely due to a number of factors which have led to variable findings with both behavioral and electrophysiologic measures. Factors contributing to the variability among studies include (1) heterogeneity of subject populations (i.e., use of different theoretical models to define populations), (2) variability in a number of procedural factors, such as the use of various types of linguistic tasks (i.e., phonological, semantic tasks, etc.) and electrophysiologic measures to assess performance in subjects with dyslexia, (3) differences in the auditory stimuli used in the experimental designs (i.e., verbal/nonverbal stimuli, synthesized/natural speech, etc.), and (4) variability in the statistical methods used for data analysis. Some questions about the age-appropriateness of the stimuli and/or tasks employed in some of the investigations have also contributed to the controversy (Mazzotta & Gallal, 1991; Frank, Seidan, & Napolitano, 1994; Lovrich, Cheng, & Drew, 1996; Tallal, 2004; Walker, Givens, Cranford, Holbert, & Walker, 2006; Cohen-Mimran & Sapir, 2006).

To date, the majority of studies investigating temporal processing skills in individuals with dyslexia have been done on adults, with only a small number of studies focusing on school-aged children or preschoolers. It is important, however, to recognize that the latter groups should be the primary groups studied if one is interested in examining the role of temporal deficits in the development of normal reading abilities.

Findings in Adults with Dyslexia

Kujala, Lovio, Lepistö, Laasonen, and Näätänen (2006) compared the mismatch negativity (MMN) responses of nine adults with dyslexia and eleven control subjects using a five-deviant paradigm varying in pitch, duration, intensity, location, and the presence/absence of a gap. The authors found an abnormal pattern of auditory discrimination in individuals with dyslexia which suggested that these individuals and control subjects processed at least some of the deviant stimuli in a different manner (e.g., the MMN was smaller for the pitch deviant in subjects with dyslexia than in controls, whereas the opposite pattern was obtained for the location deviant).

Breznitiz and Misra (2003) investigated whether an ‘‘asynchrony’’ in the speed of processing between the visual–orthographic and auditory–phonological modalities might contribute to the word recognition deficits often noted among adult dyslexics. Male university students with a history of diagnosed dyslexia were compared to age-matched normal readers on a variety of experimental measures while event-related potentials and reaction time data were collected. The experimental measures were designed to evaluate auditory and visual processing for non-linguistic (tones and shapes) and linguistic low-level stimuli (phonemes and graphemes), as well as for higher-level orthographic and phonological processing stimuli (in a lexical decision task). Results indicated that the adults in the experimental group had significantly slower reaction times and longer P300 latencies than their age-matched peers on most of the auditory tasks. In addition, they showed delayed auditory P200 latencies for the lexical decision task. Moreover, the analysis of the data for the adults diagnosed with dyslexia revealed a systematic speed of processing gap in P300 latency between the auditory/phonological and visual/orthographic processing measures. A similar difference, however, was not observed for age-matched normal readers.

In a subsequent study using auditory evoked potentials, Giraud and colleagues (2005) recorded electrophysiologic responses from eight adults with a history of development dyslexia who experienced persistent reading, spelling, and phonological deficits and ten non-dyslexic controls. The stimuli in this study included voiced and voiceless consonant-vowel syllables. Subjects with dyslexia coded these stimuli differently according to the temporal cues that formed the basis of the voiced/voiceless contrasts than the subjects from the non-dyslexic group. According to the authors, these findings revealed the presence of anomalies in cortical auditory processing which could underlie the persistent perceptual and linguistic impairments typically observed in individuals with developmental dyslexia.

Moisescu-Yiflach and Pratt (2005) also found significant differences on event-related potentials (N1, P2, N2, P3) between adults with dyslexia and adults with normal reading abilities. The adults with dyslexia presented longer latencies for linguistic and non-linguistic test stimuli that differed in their spectral and temporal characteristics. These findings suggested that the auditory processing impairments noted in individuals with dyslexia are independent of stimulus type.

Petkov, O'Connor, Benmoshe, Baynes, and Sutter (2005) used an auditory perceptual grouping task in their study that required the subjects to disentangle distinct acoustic stimuli from a complex waveform arriving at each ear (e.g., perceptually grouping the oboes and violins in a musical piece to allow one to separately attend to the melodic line of each instrument). Nine adult participants with dyslexia and ten controls were instructed to listen to a middle frequency tone within a stream of background tones. Results showed that the differences in performance between the dyslexic and control groups depended on sound frequency as well as presentation rate. The authors concluded that individuals with dyslexia have an auditory deficit that is dependent on both the spectral and the temporal features of sounds.

Tallal's 1980a study, which was discussed previously, was subsequently replicated by Protopapas, Ahissar, and Merzenich (1997) in adults with dyslexia. The results of the latter study documented that adults with reading disability also experienced auditory temporal processing deficits, which were similar in nature to the types of deficits that Tallal found for children with reading disabilities. Stein and McAnally (1995) also studied auditory processing in adults with dyslexia and demonstrated that adults in the experimental group required significantly larger stimulus changes in order to detect the rate and depth of frequency modulations of tones when compared to the performance of the adults in their control group. These researchers concluded that individuals with reading disability have an impaired ability to rapidly process auditory information.

Findings in Children with Dyslexia

Putter-Katz, Kasson-Rabin, Sachartov, Shabtai, Sadeh, Weiz, Gadoth, and Pratt (2005) assessed behavioral and electrophysiological responses of children with dyslexia and an age-matched group of children with skilled reading abilities while the children performed a set of hierarchically structured auditory tasks which consisted of verbal stimuli differing in their rates of spectral change. The authors based their study on the hypothesis that the phoneme perception deficits observed in children with dyslexia are based upon a rapid rate auditory processing deficit. In this study, two speech contrasts were examined: consonant place of articulation and vowel place of articulation. The authors found significant differences in auditory processing assessed by both behavioral and electrophysiological tasks between the two groups on these measures and concluded that the deficient auditory processing of natural speech under normal listening conditions is a contributing factor to reading difficulties in dyslexia.

Hood and Conlon (2004) investigated the ability of visual and auditory temporal processing measures (i.e., TOJ measures) obtained before school entry to predict reading development in an unselected sample of 125 children. The authors presumed that reading and temporal processing abilities were continuously variable as had been suggested by other researchers (Shaywitz et al., 1992; Talcott et al., 2000). The results showed that both visual and auditory TOJ tasks significantly predicted letter and word identification ability as well as reading rate in early Grade 1, even after the effects of age, environment, memory, attention, nonverbal ability, and speech/language problems were accounted for.

Another investigation found significantly lowered accuracy, longer reaction times, and prolonged P3 (P300) latencies using pairs of syllables that differed only by VOT (e.g., /ba/ vs. /pa/) among a Hebrew-speaking group of 10 to 13 year-old children with reading disabilities when their results were compared to those of their control peers (Cohen-Mimran, 2006). Breier, Gray, Fletcher, Diehl, Klaas, Foorman, and Molis (2001) also showed that English-speaking children with reading disability had difficulty in processing speech and nonspeech stimuli containing similar brief auditory temporal cues.

In order to examine whether individuals with reading disabilities have deficits in processing rapidly presented, serially ordered non-speech auditory signals, the performance of 12 children with reading disabilities and 12 typically developing children were compared on a task involving the ability to make same-different decisions for four different pairs of 1000 and 2000 Hz pure tones presented with short (50 msec) and long (500msec) ISIs (Cohen-Mimran & Sapir, 2006). Results showed that children with reading disabilities had difficulty in discriminating pure tones with short, but not long ISIs, whereas the controls performed well on both short and long ISIs. Furthermore, there were significant correlations between the short ISI performance and phonological awareness test results when the two groups were combined.

In another study, auditory masking thresholds were measured in fifty-two 7 to 10 year-old children (Montgomery, Morris, Sevcik, and Clarkson, 2005). Twenty-six of the children in this study were diagnosed with reading disability and 26 were typically developing readers. The results indicated that reading disability status correlated with performance on both backward bandpass noise and backward notched-noise masking conditions, suggesting that both temporal and spectral auditory processing deficits are evident in individuals with dyslexia.

Breier, Fletcher, Foorman, Klaas, and Gray (2003) administered tasks assessing the perception of auditory temporal and non-temporal cues to four groups of children: (1) children with reading disability without attention deficit/hyperactivity disorder (ADHD), (2) children with ADHD alone, (3) children with reading disability and ADHD, and (4) children with no impairment. The authors found that the presence of reading disability was associated with a specific deficit in the ability to detect an asynchrony in tone onset time, a measure of temporal resolution. However, no reduction in performance was observed in children with reading disability, but without cormorbid ADHD, on other tasks assessing perception of temporal acoustic cues, such as gap detection (GD) and binaural masking level differences. On the other hand, the presence of ADHD was associated with a decrement in performance across all tasks regardless the status of the subjects' reading abilities. This latter finding, however, was in contrast to the findings of previous studies that reported intact auditory temporal functioning as assessed by GD and masking level differences procedures in children diagnosed with ADHD (Ludlow, Culdahy, Bassich, & Brown, 1983; Pillsbury, Grose, Coleman, Conners, & Hall III, 1995).

van Ingelghem, van Wieringen, Wouters, Vandenbussche, Onghena, and Ghesquière (2001) found significantly larger GD thresholds in 11-year-old children with dyslexia when compared to normal reading children using a two-interval, two-alternative forced-choice GD paradigm. These researchers also noted that the results on the experimental task were significantly correlated with both real word reading and non-word reading measures in their subjects.

These findings were later replicated in a broader study in children with and without dyslexia matched for sex, age, and intellectual ability (van Ingelghem, Boets, van Wieringen, Onghena, Ghesquière, & Wouters, 2004). Hautus, Setchell, Waldie, and Kirk (2003) also observed larger GD thresholds in subjects with dyslexia, but found that these thresholds were only significantly larger for the young reading-impaired subjects (aged 6 to 9 years), but not for the older participants (aged 10 years up to adulthood). These authors interpreted these results as indicative of a maturational lag in the development of temporal acuity in young children with dyslexia.

A study investigating the performance of 250 individuals with dyslexia and 432 controls whose ages ranged from 7 to 22 years using a broadband GD paradigm found that the majority of the individuals diagnosed with dyslexia were unable to perform the GD task even at its easiest level (Fischer & Hartnegg, 2004). However, within the group of participants with dyslexia for whom a threshold could be determined, no difference in GD performance was noted when this group's performance was compared to the performance of the children in the normal reading group.

Benasich and Tallal (2002) administered a conditioned repetition task to 7.5 month old infants born into families who were either positive or negative for family history of language impairment. The stimuli in this study used consisted of two 70 msec duration complex tones presented with varying ISIs depending on the infants' response performance. The authors observed not only significantly poorer thresholds for children born into at-risk families, but they also demonstrated that rapid auditory processing thresholds were the single best predictor of language development at two years of age. Unfortunately, information about literacy development and its relation with rapid processing thresholds was not yet available for these children.

Studies using dynamic stimuli (i.e., stimuli that are changing in time, such as amplitude or frequency modulation) also pointed to an auditory temporal processing deficit in children with dyslexia (Menell, McAnally, & Stein, 1999; Talcott, Witton, McClean, Hansen, Rees, & Green, 1999; Rocheron, Lorenzi, Fullgrabe, & Dumont, 2002). These studies found that accurate tracking of amplitude and frequency changes was critical for the accurate perception of speech, and that deficits in both temporal and spectral analysis were evident among the children with dyslexia.

Auditory pattern recognition skills in children with reading disability were investigated in another study using perceptual tests involving discrimination of frequency and duration tonal patterns (Walker et al., 2006). Children with reading disability exhibited significantly higher error rates in discrimination of duration and frequency patterns, as well as larger brief tone frequency difference limens.

Gibson, Hogben, and Fletcher (2006) found that a group of children with dyslexia ranging from 8 to 12 years of age performed poorer when compared to age-matched typically developing peers on three measures of auditory temporal processing: frequency discrimination, frequency modulation, and backward masking. The authors, however, found no significant associations between the phonological (reading rate, accuracy and comprehension, single word and nonword reading, etc.) and the auditory temporal measures used.

Whole-brain functional magnetic resonance imaging (fMRI) studies were performed on 22 children with developmental dyslexia and 23 typically developing readers while they listened to nonlinguistic acoustic stimuli with either rapid or slow transitions that were designed to mimic the spectro-temporal structure of CVC speech syllables (Gaab, Gabrieli, Deutch, Tallal, & Temple, 2007). While the typically-developing readers showed activation for rapid as compared to slow transitions in the left prefrontal cortex, children with dyslexia did not show any differential response patterns in this region. Also, after 8 weeks of remediation focusing on rapid auditory processing, phonological, and linguistic training the children with developmental dyslexia showed significant improvements in literacy skills and exhibited activation patterns in the left prefrontal cortex that were similar to those noted in the typically-developing readers.

King, Wood, and Faulkner (2007) examined the extent to which 23 children with dyslexia differed from 23 reading age (RA) and 23 chronological age (CA) matched controls in their ability to make temporal judgments about auditory and visual sequences of stimuli, as well as in the speed of their reactions to the onsets and offsets of visual and auditory stimuli. The authors found that the participants with dyslexia were slower than the CA controls in their reactions to nonverbal auditory onsets (tones), were less able to recognize the first stimulus in a sequence of tones, and were less accurate in identifying the initial phoneme of a sequence of three phonemes, suggesting an impaired temporal processing system for rapid auditory stimuli in children with dyslexia. In the visual domain, dyslexic readers showed impairment compared to CA controls in responding to the last item in a sequence of three nonverbal visual stimuli (shapes). Although reaction times in the visual and auditory onset and offset tasks were found to be significantly intercorrelated in the control group, the dyslexic group did not show significant correlations in reaction times between the auditory and visual domains, or between the onset and offset reaction times within each modality. Based on these findings, the authors suggested the presence of a less well integrated cross-modal and intra-modal temporal system in children with dyslexia.

As stated at the beginning of this chapter, some researchers failed to demonstrate a link between dyslexia and auditory temporal processing. The results of these studies are described below.

In order to investigate the relationship between auditory temporal processing of non-speech sounds and phonological awareness ability, Tallal's TOJ task was administered to 42 children with reading disabilities (Bretherton & Holmes, 2003). The results showed a lack of relationship between tone-order deficits and sequence processing of speech sounds, poorer phonological awareness, and severity of reading difficulties.

Watson (1992) administered five auditory temporal processing tasks (tone duration, pulse discrimination, tone loudness, temporal order for tones, and syllable sequence tests) to college students with and without reading disability. Although the reading-disabled group performed more poorly on all temporal tasks, only the results on the single tone duration test reached statistical significance.

Boets and colleagues (2006) administered GD, FM-detection, and tone-in-noise detection tasks to 62 five-year-old children. Half of the participants were children of dyslexic families and the other half were control children from normal reading families. Although the subjects from families with a history of dyslexia showed abnormal performances for the GD and FM detection tasks, this tendency did not reach statistical significance. The authors hypothesized that this lack of significance might be attributed to either the greater individual variability noted among the children from the at-risk group or to the fact that a well-defined clinical group was not established in this study.

Although GD ability using pure-tone stimuli is reported to be deficient for children with reading disability (McCroskey & Kidder, 1980), other studies found no deficits among children with dyslexia for GD in broadband noise stimuli (McAnally & Stein, 1996; Schulte-Körn, Deimel, Bartling, & Remschmidt, 1999; Breier et al., 2003). Studdert-Kennedy and Mody (1995) have specifically challenged Tallal's temporal processing theory, arguing that the observed phonological impairments in dyslexics are speech-specific and cannot be attributed to a more general lower-level auditory deficit.

Heath and Hogben (2004) and Share, Jorm, Maclean, and Matthews (2002) conducted two longitudinal studies in which Tallal's repetition test (Tallal & Piercy, 1973) was administered to two different groups of preschool children who were then followed until the subjects were in second or third grade. Tallal's repetition test examines auditory temporal processing of rapid sequences by presenting two non-verbal complex sounds of high and low pitch and requiring the child to identify the tones and specify the order in which they occurred. Neither of the two groups of researchers was able to predict later grade literacy scores based solely on the auditory data that they collected from their participants during their preschool assessments.

Variations of auditory stimuli which differed in complexity and task demands were applied to three groups of 8th grade females, a normal learning control group and two learning disabled groups, one with dyslexia and another with learning problems but normal reading and phonological abilities (Banai & Ahissar, 2006). The results suggested that the extent of the difficulties experienced by the learning disabled group with dyslexia was determined by the structure of the task rather than by stimulus composition and complexity, thus implicating a working memory deficit.

It is evident that the literature has yet to provide a conclusive statement as to the relationship, causal or associated, between underlying auditory skills and reading disability. It would appear that before a more definitive statement on this relationship can be made more consistency will be needed in experimental group identification, selection criteria, and experimental parameters, which in turn would allow for more homogeneity within groups and better understanding of the development of auditory temporal processing skills in children with normal and disordered reading abilities.

Gap Detection as a Measure of Auditory Temporal Resolution

Auditory temporal resolution refers to the ability of the auditory system to detect changes in a stimulus over time or to respond to rapid changes in the envelope of a sound stimulus over time, e.g., the ability to detect a gap between two stimuli or to detect that a sound is modulated in some way (Plack & Viemeister, 1993; Moore, 1997). Auditory temporal resolution can also be defined as the shortest duration of time required to discriminate between two auditory signals (Gelfand, Hoffman, Waltzman, & Piper, 1980).

One psychophysical method and a common way of investigating temporal resolution is the GD paradigm, which was first introduced by Plomp (1964). In GD experiments, listeners are asked to detect the presence of a short interruption in an otherwise continuous sound (Schneider & Hamstra, 1999).

Boets and colleagues (2006) have suggested that the most straightforward way to measure temporal processing is the GD task, and Phillips (1999) has argued that the GD paradigm has offered more insights into auditory perception than might otherwise have been imagined, and that these insights may help advance our understanding of the nature of the speech perception process itself. This is because GD designs provide one measure of the resolution with which the stream of sound is resolved over time, and they examine the mechanisms that underlie normal and impaired temporal resolution abilities which are likely to have important roles in speech perception and its disorders (Phillips & Smith, 2004).

In many GD studies, the listener is presented with two relatively long (hundreds of msec) pure tones or noise bursts, one of which contains a brief (a few msec) silent period or “gap” at its temporal midpoint. The task of the listener in these experiments is to indicate which of the two stimuli contains the gap (Phillips, Hall, Harrington, & Taylor, 1998). In other GD studies, the listener may be presented with stimuli that are not paired, but rather consist of noise or tonal stimuli in which gaps or silent periods are randomly interspersed. In these experiments the listener’s task is to simply indicate the detection of the gap or silent period in an otherwise continuous noise segment (Musiek et al., 2005) or to indicate whether one or two stimuli are being perceived (McCroskey & Keith, 1996; Keith, 2000).

The duration of the gap is varied according to the psychophysical method employed and the purpose of these experiments is typically to find the shortest detectable gap between two noise bursts or auditory signals (Gelfand et al., 1980; Musiek et al., 2005). This is referred as GD threshold. In other words, the GD threshold reflects the shortest time interval that an individual can resolve or the shortest gap duration within a sound that a person can detect (Musiek et al., 2005). In order for a gap to be detected, the neural activity produced by an ongoing signal must decay at signal offset to a level such that the difference between it and the increase in neural activity accompanying the return of the signal would be detectable (Leitner et al., 1993). The smallest detectable gap would thus have a duration just long enough for this to occur.

Despite the diversity of techniques and species used to study temporal resolution ability, the minimum detectable gap has consistently been demonstrated to be in the range of 2 to 6 msec, defining the limit of the auditory system's ability to track rapid changes in an acoustic stimulus (Musiek et al., 2005). Studies have shown that the normal GD threshold in humans is on the order of 2 to 3 milliseconds (msec) when extensive training of the target population is employed (Green, 1985; He, Horwitz, Dubno, & Mills, 1999; Phillips, 1999; Musiek et al., 2005), whereas slightly increased GD thresholds have been shown for less trained populations (Phillips & Smith, 2004; Musiek et al., 2005).

Between-Channel Gap Detection versus Within-Channel Gap Detection

Phillips, Taylor, Hall, Carr, and Massop (1997) distinguished two different temporal processes involved in the performance of a GD task, which can be assessed using two different types of tasks: the within-channel GD task and the between-channel GD task.

In the within-channel GD paradigm, the stimulus preceding the gap is identical in spectrum and duration to the stimulus following the gap (He et al., 1999). Phillips and colleagues (1997) and Taylor, Hall, Boehnke, and Phillips (1999) argued that in this paradigm the temporal operation executed is actually a discontinuity detection within the perceptual channel activated by the sound. As such, the auditory signal preceding the gap can be expected to stimulate the same neuronal pool that would be stimulated following the gap (Bellis, 2003). Also, information about the stimulus perturbation constituting the gap can be carried by any single perceptual or neural channel representing the stimulus spectrum.

In contrast, if the sound marking the leading edge of the gap activates different peripheral neurons from those marking the trailing edge of the gap (between-channel GD case), then the temporal operation necessarily becomes a relative timing of the offset of the activity in the perceptual channel representing the leading marker and the onset of activity in the channel representing the trailing marker (Phillips et al., 1998). Phillips and colleagues (1998) also believe that this relative timing operation must be performed centrally, because the auditory periphery contains no lateral connections capable of executing the relative timing operation.

Gap detection thresholds for the between-channel condition tend to be much larger than those for the traditional within-channel GD paradigm (Phillips et al., 1997; Taylor et al., 1999; Phillips & Hall, 2000). Gap detection thresholds for the within-channel condition are usually as short as a few milliseconds (2 to 6 msec), whereas for the between-channel paradigm the shortest detectable gap can be lengthened to 10 to 50 msec, depending on the stimulus parameters (Boehnke & Phillips, 1999). The reasons for this lengthening of the GD thresholds in the between-channel GD paradigm are not known with certainty at this time. That is, it is not clear why a cross-correlation of the activity in two different channels results in a poorer acuity (i.e., an elevated threshold) than the discontinuity detection in any single channel (Phillips, 1999).

Fitzgibbons, Pollatsek, and Thomas (1974) described the between-channel operation in terms of attention switch processes in the perceptual channel activated by the leading marker and the subsequent time-consuming shifting of those processes to the channel representing the trailing one. Phillips and colleagues (1997) also proposed a role of attentional processes in that the allocation of perceptual or attentive resources to any one channel impoverishes the time stamping of events in another channel.

In a research study conducted by Phillips and colleagues (1998), six normal adults with no hearing deficits were tested for their temporal auditory GD thresholds using free-field presentation of white-noise stimuli delivered from the left and right poles of the interaural axis. They found low GD thresholds for stimuli in which the markers for the gaps had the same location (i.e., within-channel condition) and larger thresholds for stimuli delivered from different locations (i.e., between-channel case). These results suggest that a relative timing operation mediates GD when the markers activate different perceptual channels and that this timing process can operate on perceptual channels emerging from central nervous system processing. Phillips and colleagues (1997) also obtained larger GD thresholds for the between-channel case in comparison to the within-channel conditions for the same listeners, irrespective of whether the perceptual channels were defined by stimulus spectrum or by stimulus laterality (ear stimulated).

The larger GD thresholds observed in the between-channel paradigm presumably reflects the poorer central representational overlap of the markers delimiting the gap (Formby, Sherlock, & Li, 1998; Boehnke & Phillips, 1999). That is, each marker has its own representation in a spatial-temporal pattern of activity within the central auditory nervous system.

Support for this explanation of the larger GD thresholds in most between-channel paradigms is that between-channel gap thresholds approach within-channel values when the markers become sufficiently similar and coactivate neural representations whose responses can be inputted to a discontinuity detection process. In the absence of such a representational overlap, GD relies entirely on the relative timing of activity in the two channels, and GD thresholds remain high (Phillips, 1999; Phillips & Hall, 2000).

Phillips and Smith (2004) compared thresholds of 95 normal adult listeners in two within-channel and one between-channel GD paradigms and found that the two within-channel paradigms were highly correlated with each other, but the thresholds for the between-channel stimulus were weakly correlated with thresholds for the within-channel stimuli. This data provides further evidence of the separability of within-channel and between-channel GD mechanisms.

Heinrich, Alain, and Schneider (2004) examined the neural correlates associated with within-channel and between-channel GD paradigms using the mismatch negativity (MMN) wave. Even though they found larger GD thresholds behaviorally for between-channel than for within-channel GD tasks, the ability to automatically register equally discriminable within-channel or between-channel discontinuities generated comparable MMN responses.

Taylor and colleagues (1999) tested five normal listeners for their GD thresholds, using stimuli in which the narrow-band noise markers of the gap differed in one or two auditory dimensions, i.e., frequency composition and/or ear stimulated. Gap thresholds for stimuli in which the markers differed along either single dimension averaged about 18 msec, whereas thresholds for markers differing across both dimensions were closer to 28 msec. The authors suggested that although GD thresholds were poorer when both dimensions differed, the mechanisms or resources mediating the two different types of between-channel GD stimuli must be partially shared across auditory dimensions.

Phillips and Smith (2004) elected to assess GD thresholds in 95 untrained normal listeners since most of the available data on the sensitivity of the between-channel GD paradigm for assessing temporal resolution abilities had come from intensive studies involving very small numbers of highly practiced listeners (Formby et al., 1998; Phillips et al., 1997, 1998; Taylor et al., 1999; Phillips & Hall, 2002). These researchers found that the disparity often observed between the within-channel and between-channel GD thresholds in trained populations extended to a population of naïve listeners with normal hearing. In their investigation, GD thresholds of 5 to 8 msec and 28.7 msec were noted for the within-channel and between-channel conditions, respectively. Furthermore, the authors suggested that their data constituted a set of norms against which other populations, including pathological ones, could be compared. Finally, these researchers assessed GD thresholds in a sound-treated double-walled booth and in a quite room and found that there were no significant differences between GD thresholds obtained in these two listening environments.

A particularly interesting feature of the between-channel GD paradigm is that the mean of the individual gap thresholds falls in the range of durations that separate the VOTs of voiced and unvoiced stop consonants (Stark & Tallal, 1979). In 1978, Kuhl and Miller suggested that the speech system exploited naturally occurring psychophysical discontinuities in the formation of phonetic categories. Phillips and Smith (2004) hypothesized further that the perceptual category boundaries between voiced and unvoiced stop consonants might rest in part on the categorical distinction between detectable and undetectable between-channel temporal gaps. In other words, the between-channel gap threshold provides one psychophysical discontinuity in the temporal domain that might be exploited by the speech system to form VOT perceptual category boundaries.

Influence of Stimulus Parameters

By using a number of techniques and different animal species, researchers have attempted to characterize the limits of auditory temporal resolution and the factors that affect it. Experiments have involved humans (Plomp, 1964; Williams, Elfner, & Howse, 1979), the house finch (Dooling, Zoloth, & Baylis, 1978), the ferret (Kelly, Rooney, & Phillips, 1996), the rat (Ison, O'Connor, Bowen, & Borcinea, 1991), and the chinchilla (Giraudi, Salvi, Henderson, & Hamernik, 1980) as subjects. Typically, the parameters that have been manipulated include the duration of the gap, the frequency characteristics, the intensity, and the duration of the sound in which the gap is embedded, and the temporal location of the gap within the acoustic background (Forrest & Green, 1987; Nelson & Thomas, 1997; He et al., 1999; Rupp et al., 2002; Trainor, Samuel, Desjardins, & Sonnadara, 2001; Sulakhe, Elias, & Lejbak, 2003).

Gap detection thresholds vary greatly as a function of several parameters, such as the duration and spectral content of the markers, and are larger if the initial and the final markers are processed in different frequency channels (Eddins, Hall III & Grose, 1992; Hall III, Grose & Joy, 1996; Moore, 1997; Schneider & Hamstra, 1999; Trainor et al., 2001). Eddins and colleagues (1992) found that GD thresholds obtained using bandpassed noise depended more on the bandwidth of the stimulus than its center frequency. Hall and colleagues (1996) suggested that this may reflect the greater information being transmitted to the central nervous system. There is agreement among researchers that when using wide-band or high frequency signals and presenting the stimuli significantly above amplitude threshold, minimal detectable gaps are in the order of a few milliseconds (Plomp, 1964; Fitzgibbons, 1983; Shailer & Moore, 1983; Moore, Peters, & Glasberg 1993). Also, there is some evidence that the GD performance supported by the apical regions of the cochlea (i.e., low frequencies) is relatively poor (Hall III et. al. 1996; Phillips et al., 1997), especially when compared to the results obtained when testing is completed with stimuli that are supported by the basal end of the cochlea (i.e., high frequency sounds). This is likely because of the greater stimulus uncertainty that may occur for low-frequency sounds. For instance, the inherent fluctuations in the low frequency stimulus envelope might be confused with the presence of a gap (Moore et al., 1993). Finally, a study conducted by Eggermont (1995) on the cat's auditory cortical system revealed that the coding of gaps is poorer for gaps occurring early (5 msec) rather than later (500 msec) in a noise stimulus.

Phillips and colleagues (1997) conducted four different experiments on GD with normal listeners, with the purpose of examining the consequences of using different stimulus parameters to delimit the silent temporal gap. In experiment 1, subjects were presented with pairs of narrow-band noise sequences, in which the leading element in each pair had a center frequency of 2000 Hz and the trailing element's center frequency was parametrically varied. Experiment 2 assessed the effect of leading-element duration in within-channel and between-channel GD tasks. While for experiment 3, the authors redesigned the GD stimulus in order to investigate the perceptual mechanisms that might be involved in stop consonant discrimination. In this particular experiment the leading element was a wide-band noise burst that varied in duration and the trailing element was a 300 msec bandpassed noise centered at 1000 Hz. In experiment 4, the generality of the leading-element duration effect in between-channel GD was examined. Spectrally identical noises defining the leading and trailing edges of the gap were presented to the same ear or to different ears. Their general findings were (1) GD performance in between-channel paradigms was poorer than in within-channel conditions; (2) GD thresholds were poorer when the duration of the leading marker was less than about 30 msec, but only in the between-channel case; and (3) when the leading element of the between-channel condition was shorter in duration (5 to 10 msec), GD thresholds were close to 30 msec, which the authors pointed out is close to the VOTs that differentiate some voiced from unvoiced stop consonants. The authors concluded that GD requiring a temporal correlation of activity in different perceptual channels is a fundamentally different task to the discontinuity detection used to execute GD performance in the within-channel paradigm.

Musiek and colleagues (2005) discussed the merits of using a broadband stimulus versus a frequency-specific stimulus for clinical applications of the GD paradigm. They argued that the broadband stimulus may be the better stimulus to use in clinical applications of the GD paradigm as it is less likely to lead to variability across different age groups or as a function of peripheral hearing status. On the other hand, Shinn (2007) has suggested that one advantage of using tonal stimuli is that it allows the clinician to obtain frequency-specific information regarding temporal resolution skills.

Influence of Age on Temporal Resolution

It is well known today that there are differences between the performances of adults and children on many measures of auditory processing abilities. For instance, in the young child, masked thresholds are higher (Schneider, Trehub, Morrongiello, & Thorpe, 1989) and discrimination of intensity, frequency, duration, and temporal cues is poorer (Hall III & Grose, 1994; Irwin, Ball, Kay, Stillman, & Bosser, 1985; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989; Schochat & Musiek, 2006). These differences may arise from both structural and/or functional immaturities in the peripheral auditory system and the central auditory system (Hautus et al., 2003; Werner, 2007), or they may be attributable to cognitive limitations on the processing ability in the young child versus the adult.

Although the literature has documented clear age-based differences in many auditory skills, the effects of age (i.e., maturation) on GD ability in young children are not clear. There have been reports that the temporal resolution ability may still be developing in young children up to and possibly even beyond the age of 10 years (Elliott & Katz, 1980; Grose, Hall III, & Gibbs, 1993). Grose and colleagues (1993) examined both within- and between-channel GD performance in 21 children between the ages of 4 to 10 years on a temporal resolution task and found that at low frequencies temporal resolution ability continued to improve up until the age of 10 years (i.e., the upper age limit of their subjects), whereas at high frequencies performance approached adult levels by the age of 6 years. Research conducted by Irwin and colleagues (1985) with 56 children aged 6 to 12 years and eight adults found that within-channel temporal resolution improved with age, reaching adult levels by the age of 11 to 12 years. Using a within-channel two-alternative forced-choice task with broadband noise, the authors reported that at 40 dB sound pressure level (SPL), the minimum detectable gap averaged 5.6 msec for the 11 year-old children and 5.7 for the adults, and at 60 dB SPL the corresponding values were 3.6 msec for the 11-year-olds and 3.4 msec for the adults. Thus, the minimum detectable gap duration was significantly shorter at higher levels of the noise, but there were no obvious differences in the performances of the 11-year olds and the adults in their GD performance at either intensity level.

Data presented by Wightman and colleagues (1989) also suggested that children demonstrate poorer auditory temporal skills than adults. Using an adaptive forced-choice psychophysical paradigm, 20 children between 3 and 7 years of age and five adults were asked to detect the presence of a temporal gap in a burst of half-octave-band noise at band center frequencies of 400 Hz and 2000 Hz. The mean gap thresholds in the 400 Hz condition were larger for the younger children than for the adults, with the 3 year-old children demonstrating the highest thresholds. Gap thresholds in the 2000 Hz paradigm were generally lower than in the 400 Hz condition, but showed a similar age effect. The authors suggested that the mean GD thresholds of the 3- to 5-year-old children were elevated in part because of larger within-subject variability compared to that of the adult participants.

A study conducted by Grose and colleagues (1993) using a modified masking period pattern paradigm investigated age and frequency effects on temporal resolution. The findings suggested that age effects existed at both low- and high-frequency regions, but that the developmental effects for temporal resolution were more pronounced at lower frequencies. When developmental effects were present at higher frequencies, they tended to be restricted to the very youngest age groups (i.e., 3-, 4-, and 5-year-olds), whereas for low frequencies, developmental effects continued to exist until the age of 10 years.

Werner and Marean (1996) found that infants' thresholds for detecting gaps in continuous broadband noise were around ten times larger than those of adults. On the other hand, Shinn, Chermak, and Musiek (in press) reported evidence, based on the performance of children ranging in age from 7 to 18 years on a broadband noise GD test, that by the age of 7 years the temporal resolution thresholds of children had reached adult values.

Finally, Trainor and colleagues (2001), using an electrophysiological procedure (MMN), found that in infants as young as 6 months, within-channel GD thresholds at 2000 Hz were essentially at adult levels under conditions of little adaptation. The authors suggested that although their findings were in contrast to the behaviorally determined GD thresholds, it must be taken into consideration that the MMN procedure does not require a behavioral response and is elicited without the requirement that the subject attend to the stimuli.

Temporal Resolution Clinical Tools

Among the underlying assumptions for GD testing are the understanding that (1) the acoustic signals that comprise a spoken language have a basis in time; (2) the learning of these temporally bound acoustic signals requires a listening system that can detect the smallest time segment that is part of the spoken language code; (3) individuals whose auditory systems have varying degrees of temporal processing disorders will exhibit varying kinds of verbal disabilities; and (4) GD measures can provide insight into central auditory system integrity and function (specifically, temporal resolution abilities), which in turn can inform the diagnosis of a central auditory disorder (Keith, 2000; Musiek et al., 2005).

Leitner and colleagues (1993) believe that the ability to detect gaps is at least as important as is the ability to process frequency and intensity information for the comprehension of speech. Although the importance of temporal resolution testing has been established, there is a paucity of clinically feasible procedures available to measure GD thresholds. One reason is that the GD paradigm has traditionally been evaluated through classic psychoacoustic gap detection (GD) procedures. Such measures are often not feasible in a clinical setting because classic methodologies for GD assessment are often very time-consuming, making them difficult to use within a test battery or for patients or children who cannot tolerate long periods of testing (Musiek et al., 2005). Additionally, clinicians may find they do not have the instrumentation necessary to run the classic GD paradigms in the standard audiology clinic (Shinn, 2007).

Presently, there are three commercially available tests to assess temporal resolution in a clinical setting: the Random Gap Detection Test (RGDT) (Keith, 2000), the Auditory Fusion Test-Revised (AFTR) (McCroskey & Keith, 1996), and the Gaps-In-Noise test (GIN©) (Musiek et al., 2005). Another clinical test of temporal resolution, the Binaural Fusion Test (BFT), is under development but is not commercially available at this time.

The AFTR (McCroskey & Keith, 1996) measures the shortest separation between two tones that results in a listener's perception of a single stimulus rather than two separate stimuli. This minimum duration is identified as the auditory fusion threshold and is measured in milliseconds (msec). The listener's task is to indicate whether one or two distinct tones is/are heard. To do so, the listener must specify the number of tones heard, either verbally (i.e., by saying one or two) or nonverbally (i.e., by pointing to a response card or raising one or two fingers) (McCroskey & Keith, 1996).

Keith (2000) designed the RGDT, which is a revision of the AFTR (McCroskey & Keith, 1996). This test consists of four subtests differing in frequency (500, 1000, 2000, and 4000 Hz) and employs nine tone-stimuli with inter-pulse intervals ranging from 0 to 40 msec presented in pairs binaurally. The inter-pulse interval between each pair of tones increases and decreases in duration randomly. The listener's task is to indicate whether one or two distinct tones is/are heard.

It is important to mention that even though both tests require the same type of response (i.e., counting the number of stimuli perceived), the AFTR claims to measure the fusion threshold, whereas the RGDT the GD threshold. Clinically, fusion detection and GD are often used interchangeably to describe the same process (Keith, 2000); however, it is not clear whether or not the two tasks reflect the same underlying process or neurology (Chermak & Lee, 2005). No reliability studies have been reported for the AFTR and RGDT, but normative data for children, adults, and older adults are available for both tests (McCroskey & Keith, 1996; Keith, 2000).

The BFT is an experimental temporal fusion test developed by Dr. Frank Musiek (Chermak & Lee, 2005), which engages temporal resolution and binaural interaction processes. Listeners are required to attend to pairs of noise bursts presented dichotically and sequentially, with one noise burst of the pair presented first to one ear followed by the second noise burst presented to the opposite ear. The two noise bursts are separated by randomly assigned interaural pulse intervals and the listener indicates whether one or two noise bursts are heard. No data is yet available regarding the validity and reliability of the BFT. The major differences between the BFT and both the AFTR and the RGDT include the types of noise stimuli employed and the presentation mode. In other words, the BFT uses noise burst stimuli and dichotic presentation (i.e., presentation of different acoustic stimuli to each of the two ears), whereas the RGDT and AFTR use tonal stimuli and binaural presentation (i.e., simultaneous presentation of the same acoustic stimuli to both ears).

Musiek and colleagues (2005) developed the Gaps-In-Noise (GIN©) test with the purpose of providing a clinically feasible method for evaluating GD abilities in a variety of populations with special focus on those with central auditory disorders. The GIN© test consists of a practice test and four alternative test lists employing different gap randomizations. Each of the four lists consists of a different randomization of ten gap durations, from 2 to 20 msec, presented six times in each test list. Each stimulus is composed of six seconds of broadband noise containing 0 to 3 silent intervals or gaps presented monoaurally. The listener is required to respond by pressing a button each time a gap in the noise segment is detected. The GIN© has two measures of analysis, the overall percent correct and the GD threshold, which appears to yield better sensitivity and specificity than the percent correct index (Shinn et al., in press). The GIN© test, in comparison to the RGDT, is presumed to be less cognitively demanding and less vulnerable to language interference since it doesn’t require either a counting response or a response involving speech and language production (Chermak & Lee, 2005).

Musiek and colleagues (2005) validated the GIN© test as a clinical tool for auditory temporal resolution assessment by comparing the performance of a group of 50 normal listeners with the performance of 18 subjects with confirmed neurological involvement of the central auditory nervous system. They found significantly larger GD thresholds and smaller percentages of correct responses for the group with confirmed neurological involvement, with the GIN© test demonstrating a sensitivity between 70 to 80% for central auditory nervous system lesions. The authors reported mean GD thresholds and percent correct responses on the order of 4.8 msec and 70.2% for the left ear and 4.9 msec and 70.3% for the right ear.

Sammeli and Schochat (2008) investigated the GIN© test performance of 100 normal hearing Brazilian young adults between 18 and 31 years of age and found a mean GD threshold of 4.19 msec and mean percent correct identification response of 78.89% for both ears. The authors also analyzed the subjects' GD performance in each of the four lists and reported the following A.th. results: 4.10 msec (.66 SD) for list number 1, 4.25 msec (.69 SD) for list number 2, 4.19 msec (.53 SD) for list number 3, and 4.22 msec (.61 SD) for list number 4. For the percentage of correct identification index, they found mean performance scores of 79.33% (6.06 SD) for list 1, 78.5% (5.92 SD) for list 2, 78.78% (5.38 SD) for list 3, and 78.98 (5.94 SD) for list number 4. Based on these findings the authors concluded that the four lists included in the GIN© test were equivalent.

The GIN© test was one of the four tested in the Chermak and Lee study (2005) mentioned earlier that was administered to 10 bilaterally normal hearing and normally developing children, with a mean age of 8.7 years. Performance of these subjects on the GIN© test (i.e., mean = 4.6, SD = 1.07 for the right ear; mean = 4.9, SD = 0.99 for the left ear) was consistent with the GD thresholds described in the literature for normal adult subjects (Musiek et al, 2005).

In order to investigate the feasibility of the GIN© test in the pediatric population, Shinn and colleagues (in press) assessed 72 normal children ranging in age from 7 through 18 years of age divided into 6 groups: 7-7.11, 8-8.11, 9-9.11, 10-10.11, 11-11.11, and 12-18 year olds. Each of five groups of subjects from the younger age groups (i.e., from 7 through 11 years of age) consisted of 10 subjects, whereas the 12 to 18 year old group consisted of 22 participants. The authors reported no statistically significant differences between GIN© thresholds among age groups or between ears within each age group. For children in the 8 and 9 year old groups, which represents the age range of the children who will participate in the present investigation, the mean GD thresholds and standard deviations were 5.0 msec (1.0 SD) for the right ear and 4.73 msec (1.0 SD) for the left ear in the 8-year-old group and 4.6 msec (.84 SD) for the right ear and 5.1 msec (1.37 SD) for the left ear for the 9-year-old-group. Finally, no developmental effect was seen in GD thresholds across the groups, which suggests that children as young as 7 years of age are able to complete the GIN© with no significant difficulty and that they tend to perform at levels consistent with those observed in normal adults.

Since the GIN© test (Musiek et al., 2005) is of special interest in the present study, it is important to mention that this test has characteristics of both within- and between-channel GD paradigms as it doesn't hold all the classic parameters of the within-channel paradigm described in the literature (Phillips et al., 1997; He et al., 1999). For instance, in the typical within-channel paradigm the stimulus preceding the gap is identical in spectrum and duration to the stimulus following the gap. This is not the case for the GIN© test as the gaps (0 to 3 in number per noise segment) are randomly inserted within the 6-second noise segments. Therefore, the broadband noise stimuli that precede and follow the gaps are not all equal in duration. Hurley and Fulton (2007) suggested that the GIN© test (Musiek et al., 2005) represents a new GD paradigm since in any particular noise segment, the location and duration of the individual gaps are randomized.

Chermak and Lee (2005) compared the performance of 10 normally developing children on the four temporal resolution tests described above and observed that, from a clinically point of view, these tests were equivalent in classifying normal children appropriately. They found statistically significant differences among GD and fusion mean thresholds, but attributed this result to differences in task, stimuli, and mode of presentation across the four tests. The authors also argued that although administering and scoring the GIN© test may be more challenging initially, this test presents a number of advantages over the other three assessment tools. These include (1) the GIN© test presents strong validity as a true measure of temporal resolution since it does not require a counting or verbal response from the listener and thereby minimizes potential confounds (Jerger & Musiek, 2000), (2) it is presented monaurally, which may provide laterality information, (3) its GD threshold is defined as the shortest inter-pulse interval detected on four of six trials (67%), which is more consistent with customary definitions of thresholds as a probability of response between no response (0%) and 100% response, and (4) preliminary studies have demonstrated good reliability and sensitivity and specificity of the GIN© test when administered to patients with confirmed neurological lesions of the central auditory nervous system and to normally hearing subjects (Musiek et al., 2005). Finally, another important advantage of the GIN© test is that unlike some of the other temporal tests that are available for clinical use, it allows comparisons for follow-up testing and for assessing treatment effectiveness as there are four different but equivalent lists available (Shinn, 2007).

Summary

As discussed in Chapter 1, reading and writing is a complex activity that involves a dynamic interplay of multiple sensory and cognitive-linguistic processes. Deficits at any level might interfere with normal literacy development. Thus, the utilization of a test battery which includes both cognitive and perceptual tests is essential for the proper classification and assessment of the several clinical manifestations of reading disabilities. Given that auditory temporal processing deficit (and in particular, auditory temporal resolution deficit) is a factor that has been associated with dyslexia (either casually or comorbidly), it is important to include a temporal resolution measure when assessing literacy problems. Unfortunately, until recently there were no clinically viable measures assessing temporal resolution ability for a number of reasons. The majority of methods available involved the traditional GD paradigms that often employed abstract concepts and required long test sessions and high levels of concentration and attention, rendering them difficult to use within a test battery or for patients or children without the cognitive skills needed to understand the task or the motivation and perseverance to complete the lengthy testing procedures. Moreover, none of the early tests available for clinical use provided reliability data.

A more recently developed test (the GIN© test, Musiek et al., 2005), however, has addressed some of these shortcomings and the available research suggests that this is a viable diagnostic tool for the assessment of temporal resolution in the clinical setting. The GIN© uses interrupted broadband noise which makes it relatively resistant to peripheral hearing loss and less likely to lead to variability across different age groups for the reasons that have been discussed in depth above. The GIN© test is easily administered, not very time consuming, and it has been proven to be clinically feasible in both the adult and pediatric populations. It also has good test-retest reliability and it has yielded good sensitivity to central auditory nervous system dysfunction in the adult population. In regard to the pediatric population, the GIN© has been administered to normal children with the purpose of investigating its suitability for testing your children and to collect normative data. To date, however, no studies have been conducted with the GIN© test in children with reading disabilities or other developmental disabilities.

Therefore, the goal of the present investigation was to examine the ability of the GIN© test to differentiate between normal reading children from two groups of children with dyslexia, one composed of children with significant phonological deficits and a second group composed of children with documented reading disabilities but with no evidence of phonological difficulties or with only mild phonological processing deficits. Given that reading disabilities have been shown in a number of well-designed research investigations to involve multiple sensory systems and cognitive mechanisms, including auditory temporal processing, the GIN© test presents itself as a promising clinical procedure to be used in the assessment of dyslexia.

CHAPTER 3
METHODOLOGY

Statement of the Problem

The present study investigated the ability of the GIN© test (Musiek et al., 2005), an auditory temporal processing assessment test, as a procedure to differentiate a group of 8- to 9-year-old children with dyslexia and significant phonological awareness deficits from two different groups of children: one composed of normal reading peers and the other composed of children who had been diagnosed with dyslexia, but who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits as evidenced by normal performance on a composite score of phonological processing, but isolated deficits on one or more of the phonological processing subtests.

Since subtypes of dyslexia are yet to be determined by research findings, consistency is needed in experimental group identification. Therefore, restricted criterion and parameters must be employed to allow for more homogeneity within groups and to provide for a more accurate differentiation between or among groups so that a better understanding of the development of auditory temporal processing skills in children with normal and disordered reading ability can be gained.

The literature regarding the relationship between reading disability and auditory temporal processing deficits provided anatomical and experimental evidence that auditory temporal processing skills need to be considered when studying children and/or adults with dyslexia. As was discussed in the previous chapters, reading disability represents a heterogeneous group of disorders, the full scope of which cannot be elucidated unless a number of distinct assessment tools are employed. Thus, classifying individuals based solely on their phonological processing profiles would be insufficient since recent research findings have provided evidence of auditory and even visual problems in some individuals with reading disability. If an exact profile of the difficulties experienced by individuals with dyslexia is not determined, researchers and clinicians will not be able to identify areas of weakness and strength, and consequently they will not be able to provide effective, comprehensive, and appropriate remediation techniques.

Since auditory processing and phonological processing deficits have been shown to exist in children and adults with dyslexia, it is important to identify experimental subgroups among the population of individuals with dyslexia so that one can investigate whether the presence of these two deficits in dyslexia are connected or not. For instance, Galaburda and colleagues (1985), Humphreys and colleagues (1990), Galaburda (2002), Veuillet and colleagues (2007), and Hoen and colleagues (2008) have identified anatomical changes and differences in functionality in auditory cortical areas and other auditory relay nuclei responsible for sound processing as well as changes in the frontal lobe areas that are responsible for phonological processing in individuals with dyslexia. Questions remain, however, as to whether or not these observed anatomical changes are connected in some manner (i.e., is there a cause and effect relationship between the changes noted in these two anatomical areas) or do the changes occur independently of each other (e.g., are they simply comorbid conditions)? It is possible, if not likely, that researchers who argue that auditory temporal processing deficits should not be considered a major etiological factor in dyslexia because not all dyslexics display them (Ramus et al., 2003; Rosen, 2003) are overlooking a secondary, if not a primary, deficit area in a large subset of the population of individuals with reading disability. Unfortunately, previous dyslexia classification paradigms described in the literature have proven to be inadequate. For these reasons, the present study did not use existing classification systems to assign participants with reading disability to a group membership, but rather it utilized an alternative classification system for categorizing participants with reading disability, which as has been described above, was based on the presence or absence of significant phonological processing disorders.

Hypotheses

The GIN© test, which represented the experimental procedure in this study, was designed to differentiate those individuals with auditory temporal resolution processing difficulties from those without such difficulties. Both the control subjects and the experimental subjects with reading disability, but who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits were expected to perform better on the GIN© test, when compared to the dyslexic group with more severe phonological deficits; i.e., the first two subject groups mentioned above were expected to show smaller GD thresholds and higher percentages of correct responses than the participants with dyslexia and obvious phonological processing deficits. This expected outcome was based on evidence that indicates that language is learned, at least in the early stages of development, primarily through the auditory modality. Hence, the development of phonological skills is also likely to be influenced by auditory processing abilities. Therefore, it follows that deficits in auditory processing would negatively impact phonological abilities, which in turn would contribute to the development of reading and writing disabilities. Another possible outcome was that the two experimental groups (i.e., both participant groups with diagnoses of dyslexia) would show no significant differences on GIN© test measures, but both groups would perform poorer than the control group on these measures of temporal resolution. This would suggest that phonological awareness disorders and auditory temporal processing deficits are both part of the difficulties experienced by individuals with dyslexia, but that these two deficit areas are likely to be independent of each other. For the purposes of this investigation the following two null hypotheses were tested.

$H0^1$: There will be no significant differences in the GD thresholds as assessed by the GIN© test for the control participants and the two experimental groups; i.e., individuals with dyslexia with no or mild evidence of phonological awareness difficulties and participants with more severe phonological awareness deficits.

If this null hypothesis was to be rejected and significant differences in GD thresholds were noted between the individuals with dyslexia and more severe phonological awareness difficulties and the control subjects and the participants with dyslexia but with no or mild evidence of phonological deficits, it would suggest that the presence of phonological awareness difficulties is correlated with the presence of auditory temporal processing deficits as measured by GD thresholds. On the other hand, if this null hypothesis was rejected because significant differences in GD thresholds were observed between the control group and both groups of participants with dyslexia (i.e., no significant differences in GD thresholds were noted between the dyslexic groups), it would suggest that phonological awareness disorders and auditory temporal processing deficits are both part of the difficulties experienced by individuals with dyslexia, but that these two deficit areas are likely to be independent of each other (i.e., that they exist as comorbid conditions, but are not related to each other in some causal relationship).

$H0^2$: There will be no significant differences in the percentages of correct responses as assessed by the GIN© test for the control participants and the two experimental groups; i.e., individuals with dyslexia with no or mild evidence of phonological awareness difficulties and participants with dyslexia with more severe phonological awareness deficits.

If this null hypothesis was to be rejected and significant differences in the percentages of correct responses were noted between the individuals with dyslexia and more severe phonological awareness difficulties and both the control and participants with dyslexia with no or only mild evidence of phonological deficits, it would suggest that the presence of phonological awareness difficulties is correlated with the presence of auditory temporal processing deficits as measured by the percentages of correct responses. On the other hand, if this null hypothesis was rejected because significant differences in the percentage of correct responses were observed between the control group and both groups of participants with dyslexia (i.e., no significant differences in the percentage of correct responses are noted between the two dyslexic groups), it would suggest that phonological awareness disorders and auditory temporal processing deficits are both part of the difficulties experienced by individuals with dyslexia but the presence of one of them is not a necessary condition for the presence of the other.

Methods

The presence of auditory temporal processing deficits in children with dyslexia and typically developing children was investigated using the GIN© test, a new auditory temporal resolution measure.

Participants

Three groups of subjects participated in this study. The first group, **GROUP I**, was composed of 31 children with dyslexia and confirmed phonological awareness deficits, who ranged in age from 8 years, 1 month to 9 years, 11 months. The second group, **GROUP II**, was composed of 30 children with dyslexia from the same age-range who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits as evidenced by normal performance on the composite score of a phonological processing test, but isolated deficits on one or more of the phonological processing subtests. The third group, **GROUP III**, which served as the control group, included 30 children, ranging in age from 8 years, 0 months to 9 years, 11 months, with normal reading skills.

This age range for the participants was selected because (1) at this age, children have the attention and cognitive skills necessary to perform the task at hand, thus avoiding potential problems with the age-appropriateness of the stimulus materials and task demands (Lovrich et al., 1996; Tallal, 2004; Walker et al., 2006), (2) the classification of reading disability can be made with temporal stability (Shaywitz et al., 1992), and (3) children without disabilities at this age would be expected to have normal temporal resolution abilities as described by Hautus and colleagues (2003) and described earlier in this study.

Participants for the current investigation were selected according to the following criteria. Each participant must have or demonstrate:

- Portuguese as a first language;
- membership in a middle or upper middle class family;
- no history or evidence of behavioral, emotional, or neurological problems, with the exception of dyslexia (according to previous assessments and/or teacher and parental report);

- no history or evidence of attention, hyperactivity, and/or impulsivity problems;
- right-handedness;
- normal intelligence levels as assessed by an IQ evaluation, Wechsler Intelligence Scale for Children III – WISC III (Weschler, 1991);
- normal or corrected-to-normal vision;
- peripheral hearing within normal limits as defined as hearing thresholds of 15 dB HL or better at the octave frequencies between 250 Hz and 8000 Hz;
- normal middle ear function; and
- normal acoustic reflexes.

Groups I and II were recruited from the *Associação Brasileira de Dislexia - ABD* (i.e., Brazilian Dyslexic Association), an organization affiliated with the International Dyslexia Association, which is dedicated to the assessment of individuals with reading problems. The subjects with dyslexia were recruited either at the time of their evaluation, or for those who had already completed the assessment process, through a follow-up contact based on their evaluation results. The assessment battery used at *ABD* includes patient history, phonological awareness tasks, general motor skills, oral and written communication tests, and intelligence abilities estimation.

After being diagnosed as reading disabled, the composite score obtained on the *Perfil de Habilidades Fonológicas* (i.e., Phonological

Abilities Profile) (Carvalho, Alvarez, & Caetano, 1998) was used to determine to which group the participants would be assigned. The *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998) consists of the following tasks: analysis, blending, segmentation, deletion, substitution, rhyme reception, rhyme sequence, syllable reversal, and articulatory image. Normative data for the *Perfil de Habilidades Fonológicas* was established for 180 Brazilian children with normal reading development ranging in age from 5 years, 0 months to 10 years, 11 months, separated in 6 groups with 30 children each.

Participants with a diagnosis of dyslexia who performed below normal limits on the *Perfil de Habilidades Fonológicas* as determined by composite scores that fell below normal limits for their age range were included in **GROUP I,** and those who had been diagnosed as having dyslexia, but who performed within normal limits as measured by the composite score on the *Perfil de Habilidades Fonológicas* were assigned to **GROUP II**. Although a normal composite score was required for a participant's inclusion in Group II, normal performance on each of the subtests was not a requirement for inclusion. Therefore, it was possible for a subject to demonstrate some isolated deficits on one or more phonological processing subtests and still be included in this experimental group.

The control group, **GROUP III**, was recruited from a private middle-class school in São Paulo. Besides the characteristics described above, the students were required to demonstrate reading skills at expected grade- and age-levels. Each participant also underwent an assessment of his or her phonological processing skills using the same assessment tool as was used in the assessment of children diagnosed with dyslexia (i.e., the *Perfil the Habilidades Fonológicas)* and only those who performed within normal limits on the phonological measures assessed by this test were included in the control group.

Full approval for this study was obtained from both the Institutional Review Boards at the University of Massachusetts Amherst and at the *ABD* and only those children whose parents or guardians signed a consent form, following a full explanation of the investigation being conducted, participated in the study.

Procedures and Stimuli

Participants in Groups I and II were tested in a private clinic while seated in a double-walled, doubled-floored sound-treated booth. The testing occurred in one session, during which the assessment of hearing sensitivity and middle ear function were completed and the GIN© test (Musiek et al., 2005) was administered. After completion of these audiological tests, participants were directed to a quiet room where they completed the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998). Although the participants in the two experimental groups (Groups I and II) had previously been administered the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998) as part of their assessment testing for dyslexia, the test was readministered to these individuals during the experimental test session as the results from this test were important for determining group membership and subsequent data comparison between and among these two groups and the control group.

The children in Group III were tested in their school while seated in a double-walled, double-floored sound-treated booth housed in a quiet room in the school building. All testing occurred in one session during which time the assessment of hearing sensitivity and middle ear function was completed, and the GIN© test (Musiek et al., 2005) and the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998) were administered.

Audiological testing: Hearing thresholds from 250 Hz to 8000 Hz were obtained using a GSI 61 (Grason-Stadler, Inc.) and a Beta 6000 (Betamedical) diagnostic audiometer and TDH-39 earphones for Groups I and II and Group III, respectively. In order to examine middle ear function and acoustic reflexes, the GSI 38 immittance unit was used for all groups.

Gaps-in-Noise testing: The GIN© test (Musiek et al., 2005) stimuli, which were previously recorded on a compact disc (CD), were played on a Toshiba RG 8158BCD CD player and passed through the speech circuitry of a GSI 61 diagnostic audiometer to TDH-39 matched earphones for Groups I and II and of a Beta 6000 diagnostic audiometer to TDH-39 matched earphones for Group III. The stimuli were presented at 50 dB sensation level (SL) re: the participant's three frequencies pure tone average to each ear independently and the test duration was approximately 17 minutes for each participant.

The GIN© test (Musiek et al., 2005) is a commercially available test that is composed of a series of 6-second segments of broadband noise containing 0 to 3 silent intervals or gaps per noise segment. The interstimulus interval between successive noise tokens (segments) is five seconds in length and the gap durations presented are 2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 msec. Both gap durations and the locations of gaps within the noise segments were pseudo-randomized in regard to their occurrences. In addition, the number of gaps per noise segment was varied. These variances in the number, duration, and placement of the gaps were incorporated as a test feature in the GIN© test to decrease both the probability of "guessing" correctly and the number of trials needed to obtain statistically significant information. Ten practice items preceded the administration of the test items.

The noise used in the test was a computer-generated white noise which was uniformly distributed between -32000 and 32000 with an RMS value of 32000/sqrt(2). The sampling rate was 44,100 Hz. Therefore, the limits of the noise was defined by the transducer employed in this study (TDH-39). The noise was turned on and off instantaneously; hence, the gap durations reported above specify the durations of the silent intervals that were interspersed in the noise segments. The shortest interval between two consecutive gaps always exceeded 500 msec. The test was constructed so that there were six tokens for each gap duration in each list and there were four lists available for testing. Spectral and time displays of a 6-second noise segment with representative gaps, as well as an example of three GIN© items are shown in Figure 1.

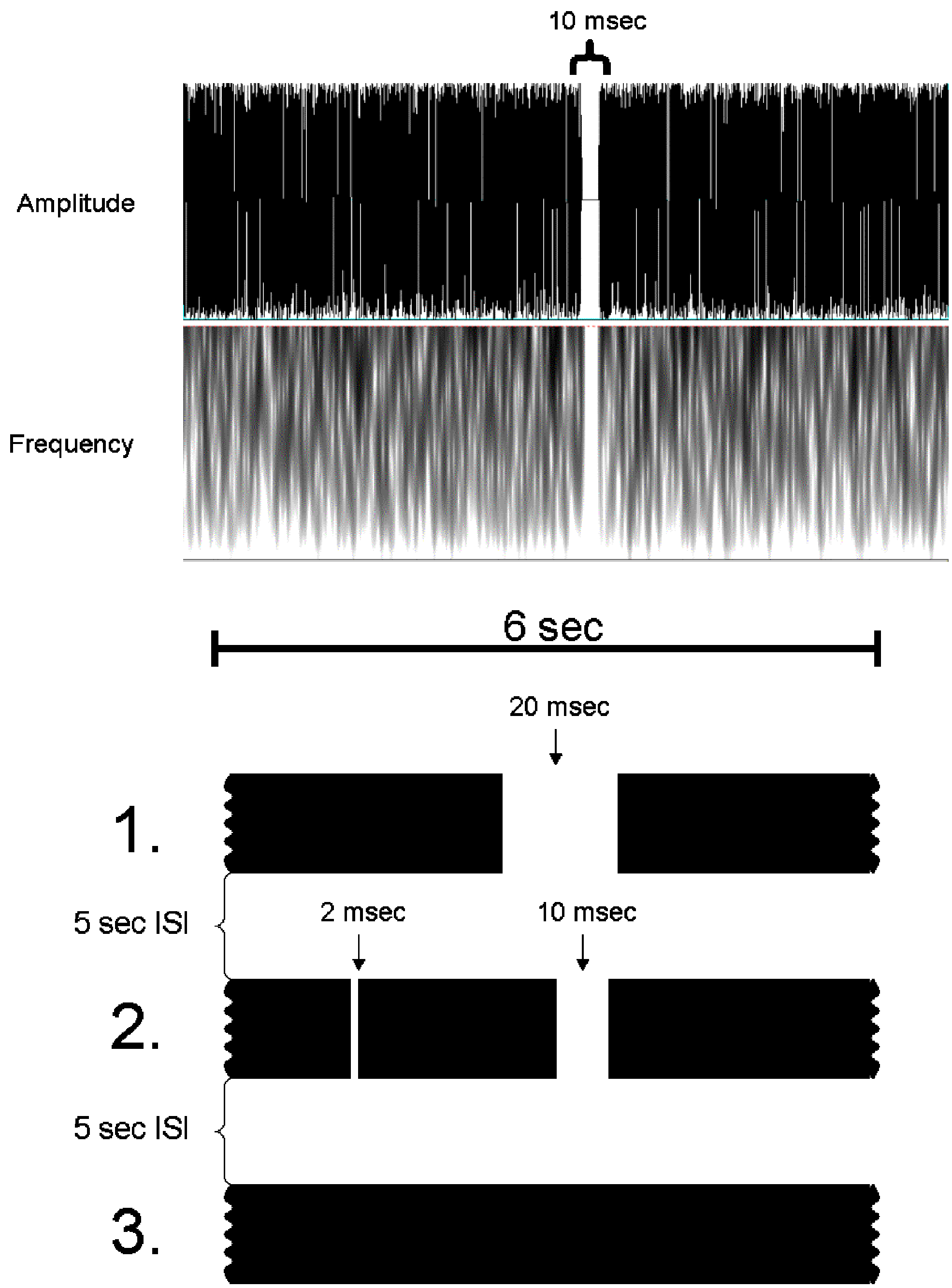

Figure 1. Spectral and time displays of a noise segment with representative gaps (upper panel) and samples of three GIN© items demonstrating the durations of the stimuli, inter-stimulus intervals, and varying gap durations (lower panel).

Two of the four lists were administered to each participant after the completion of ten practice items. The practice items were used to ensure that the participants understood the task at hand and that they were comfortable with the use of the response switch (i.e., a push button switch that the participants were asked to depress when they perceived a gap or silent period in any of the noise segments). Inter-list equivalency and test-retest reliability were previously established in the study conducted by Musiek and colleagues (2005). The presentations of the lists were randomized across participants.

The participants were instructed to press the response button as soon as they perceived a gap or a silence in the noise segments presented. If the response button was not pressed when a gap occurred, it was counted as a "missed" item or an error. If there was any confusion regarding the appropriateness of a response, the examiner asked the participant how many gaps were detected in the previous noise segment to confirm the number of responses.

A score sheet which provides the noise segment number, the time interval at which the gaps occurred, and the durations of the gaps in each noise segment was used by the examiner to record the participants' responses (Figure 2). Two measures were derived for each ear during the procedure. These included an approximated GD threshold (referred to here as the approximate threshold – A.th.) and a combined percent correct identification score across all gap durations. The A.th. was defined by Musiek and colleagues (2005) as the shortest gap duration for which there were at least *"four out of six"* correct

Scoring

	Location (ms)	Duration (ms)
1.	3870.3	20
2.	1303.2	~~2~~
	4357.6	10
3.		

Scoring

Threshold	2 msec	3 msec	4 msec	5 msec	6 msec	8 msec	10 msec	12 msec	15 msec	20 msec	Total % Score
List 1	0 /6	1 /6	3 /6	4/6	6 /6	6 /6	6/6	6 /6	6 /6	6/6	39/60
Left Ear	0%	17%	50%	67%	100%	100%	100%	100%	100%	100%	65%

ATh = 5 msec

65% Correct

Figure 2. Representation of a sample score sheet for the GIN© test. The upper panel shows the score sheet for three test items corresponding to the three test items presented in Figure 1. The location or elapsed time (in msec) within the 6-sec noise segments where the gaps occurred and the duration of the gaps segments are included on the test form. Example number one has one gap, example two has two gaps and example three has no gaps. The lower panel provides an example of a completed score sheet showing the ear tested, the numbers and percentages of correctly identified gaps at each gap duration, the combined number and percentages of correct responses across all gap durations, and the approximate threshold (A.th.).

identifications. In order to be considered the A.th, this level of performance had to be maintained (or improved) for gaps of greater durations. If a subject obtained a *"four out of six"* level of performance at one gap duration, but his/her performance slipped for gaps that were longer in duration, the initial level was not recorded as the A.th. Rather the initial performance level that yielded a *"four out of six"* correct performance level that was maintained for longer gap durations was considered the participant's A.th. The percentage of correct responses out of the total number of gaps presented in the test was also determined for each ear. Therefore, the GIN© test had two indices to measure auditory temporal performance, the A.th. and the percentage of correct responses.

Phonological processing testing: Following the completion of the GIN© test, the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998) was administered. This test was used to determine the phonological awareness profiles of the participants. It is composed of the following tasks: (1) analysis, in which the participants are asked to identify the first, middle, or final syllable of two and three syllable words; (2) blending, in which the participants are required to combine syllables and isolated phonemes of two and three syllable words; (3) segmentation, in which the participants are required to clap their hands for each word of a sentence or for each syllable of a word that they perceived; (4) deletion, in which the participants have to repeat a word omitting a whole syllable or only a phoneme of a word; (5) substitution, in which the participants are asked to replace either a syllable or a phoneme of a word with another syllable or phoneme to form a different word; (6) rhyme reception, in which the participants have to decide whether two different words rhymed or not; (7) rhyme sequence, in which the participants are required to repeat increasingly longer sequences (from 2 to 6 words) of two-syllable rhyming words, e.g., mala – bala; mala – bala – fala, etc. (a parallel item in English would be: teacher – creature; teacher – creature – preacher, etc.); (8) syllable reversal, in which the participants hear two or three syllables and are required to put these syllables in the right order to form a word; and (9) articulatory image, in which participants are asked to point to one out of four different images of a mouth, based on the first movement the mouth would make when pronouncing specific words. Individual subtest scores were obtained and a composite score based on overall test performance was derived for each participant. The maximum score for the composite test measure for this test was 76 points, and the expected performance range based upon the established norms for this test for 8 year-olds was from 55 to 68 points and for 9 year-olds it was from 59 to 71 points.

As noted above, group assignments for the participants previously diagnosed with dyslexia were made based upon the composite score. For the participants who were typically developing readers, a composite score falling within the normal range, as well as normal performance on all of the subtests, was required for inclusion in the control group.

Statistical Analysis

Descriptive statistics, including means, standard deviations, medians, and minimum and maximum scores were derived for both of the GIN© test indices (A.th and percent correct identification) and for each of the subtests of the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998), as well as for the composite score on this latter test. These data were then subjected to statistical testing.

A repeated-measures analysis of variance (ANOVA) (Neter, Kutner, Nachtsheim, & Li, 2005) was employed to test for group and/or ear differences on both GIN© test measures. The Tukey procedure was used when necessary to avoid Type I errors and the threshold logarithm of the A.th. measure was used in order to minimize major deviations from the normal distribution. The level of significance of 0.05 was fixed for all analyses.

To examine the interrelationships between both GIN© test measures and each phonological awareness subtest of the *Perfil de Habilidades Fonológicas* (Carvalho et al., 1998), Spearman's correlations (Fisher & van Belle, 1993) were computed. The level of significance of 0.05 was fixed for all correlation analyses.

Discriminant analysis (Conover, 1971; Daniel, 1995) was used to determine whether the two GIN© test indices, A.th. and percentage correct identification, were capable of differentiating the three groups participating in this study.

Finally, a reference value (Boyd & Harris, 1995), as is typically done for clinical test measures, was computed to determine normal or abnormal performance for the two GIN© test indices. For the purposes of this study, reference values were established based upon the mean performance values plus two standard deviations for each of the two indices independently.

CHAPTER 4
RESULTS

The present investigation examined the ability of the GIN© test as a procedure to differentiate a group of 8- to 9-year-old children with dyslexia and significant phonological awareness deficits from two different groups of children: one composed of normal reading peers and the other composed of children who had been diagnosed with dyslexia, but who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits as evidenced by normal performance on a composite score of phonological processing, but isolated deficits on one or more of the phonological processing subtests.

Approximate Threshold (A.th.) Comparisons Between Groups

Descriptive statistics for the A.th. measure on the GIN© test for Groups I, II, and III are displayed for both the right ear (RE) and left ear (LE) independently in Table 1 and Figure 3. An inspection of this data revealed the longest mean A.ths. for Group I (8.5 msec for the RE and 8.0 msec for the LE), while intermediate mean values were noted for Group II (4.9 msec for both ears), and the shortest mean A.th. values were noted for Group III (4.2 msec for the RE and 4.3 msec for the LE). One individual from Group I showed a RE A.th. of 15 msec, which was considered a discrepant result based on the performance of the sample, as shown in Figure 3. Closer inspection of data presented in this figure revealed that there was some overlap in the distributions of scores for Groups II

Table 1. Descriptive statistics for the GIN© test A.th. measure (msec) for the right and left ears of Groups I, II, and III.

Ear	Group	N	Mean	Std. Dev.	Minimum	Median	Maximum
Right	I	31	8.5	1.7	6	8	15
	II	30	4.9	0.5	4	5	6
	III	30	4.2	0.6	3	4	5
Left	I	31	8.0	1.5	6	8	10
	II	30	4.9	0.5	4	5	6
	III	30	4.3	0.5	3	4	5

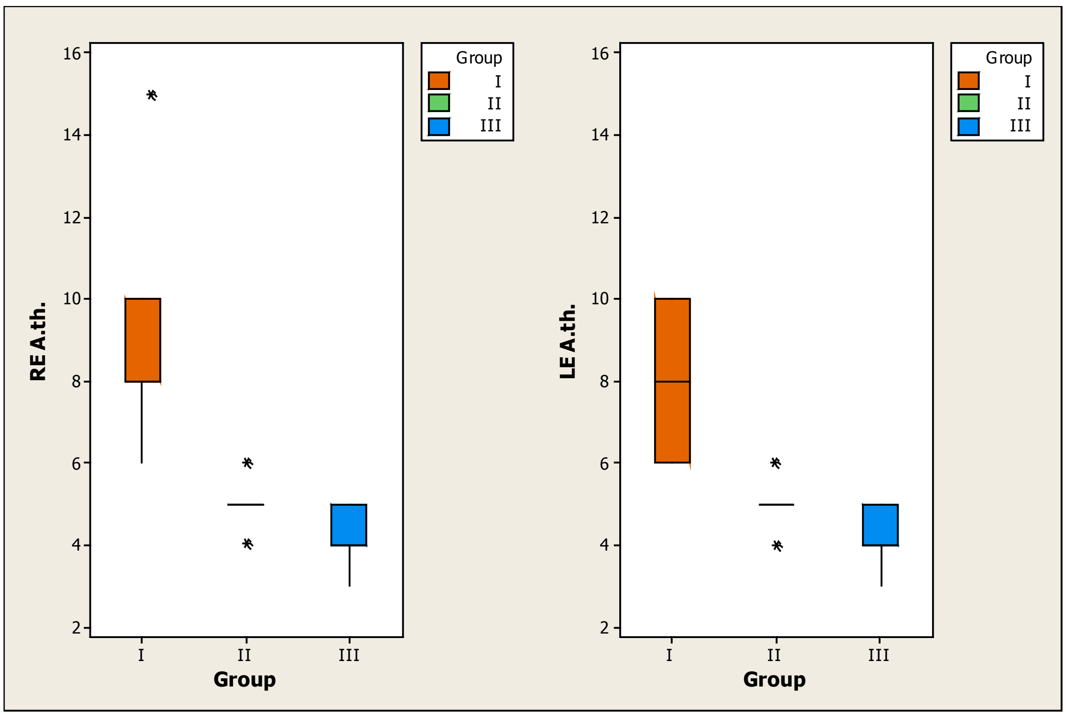

Figure 3. Box-plots for the GIN© test A.th. measure (msec) for the right and left ears of Groups I, II, and III.

and III, while there was little or no overlap in the distributions of the scores for these two subject groups and Group III. The data also showed that performance of Group II was very homogeneous in contrast to the performances of Groups I and III, suggesting minimal A.th. variability among the participants in this group.

Results of the repeated-measures ANOVA used to compare A.th. measures for each group and the two ears showed no significant differences ($F_{1,88}$ = 0.349; p = 0.556) between mean A.th. for the RE and LE, independent of group ($F_{2,88}$ = 1.90; p = 0.156), which indicates similarity of responses between ears. On the other hand, the mean A.ths. for the three groups were significantly different ($F_{2,88}$ = 234.8; p = 0.000), which was a somewhat unexpected finding. Group III showed a significantly shorter mean A.th. than did Group II (t_{88} =4.8; p = 0.000) or Group I (t_{88} =20.6; p = 0.000) and Group II showed a significantly shorter mean A.th. than did Group I (t_{88} =15.8; p = 0.000). These findings must be carefully examined because when there is not much variation in the variable being analyzed within a group, small amounts of variability in results between groups can account for statistically significant differences. Thus, even though significant differences were found for the A.th. measure among the three groups, a critical review of Figure 3 makes it evident that the performance of Group II was more similar to the performance of Group III than to the results obtained for Group I. Also, as presented in Table 1, the mean A.ths. of Group II were closer to those of Group III than to those of Group I, which had mean A.ths. for the right and left ears that were almost twice as long as those of Groups II and III.

Percent Correct Identification Comparisons Between Groups

Descriptive statistics for the GIN© test percentage correct identification measure for Groups I, II, and III are presented for both the RE and LE independently in Table 2 and Figure 4. An inspection of these data revealed the highest mean percentage correct responses for Group III (78.3% for the RE and 78.1% for the LE), with intermediate mean values noted for Group II (73.9% and 73.6% for the RE and LE, respectively), and the lowest mean percentage correct response values noted for Group I (52.9% for the RE and 54.1% for the LE). A review of the data presented in Figure 4 showed that there were discrepant performances on this measure in both Groups I and II. In terms of the percent correct identification scores, there was no overlap in the distributions of scores for Groups I and II and some overlap in the distributions of scores for Group II and Group III. As was the case for the A.th. measure, Group II's performance on this GIN© measure showed less variability when compared to that of both Groups I and III (Figure 4).

Results of the repeated-measures ANOVA used to compare the percentage correct identification measures for each group and ears showed no significant difference ($F_{1,88} = 0.18$; $p = 0.672$) between the mean percentages of correct identification scores for the RE and LE, independent of the group ($F_{2,88} = 0.831$; $p = 0.439$). These results suggest that regardless of group assignment, temporal resolution is processed in the same manner in both auditory channels (i.e., if normal performance is noted in one ear, then the performance of the other ear tends to be normal and vice versa).

Table 2. Descriptive statistics for the GIN© test percentage correct identification measure (%) for the right and left ears of Groups I, II, and III.

Ear	Group	N	Mean	Std. Dev.	Minimum	Median	Maximum
Right	I	31	52.9	5.1	40.0	55.0	60.0
	II	30	73.9	3.1	66.6	73.3	81.6
	III	30	78.3	4.3	71.6	77.5	88.3
Left	I	31	54.1	5.4	45.0	55.0	63.3
	II	30	73.6	3.6	65.0	73.3	81.6
	III	30	78.1	4.7	68.3	78.3	86.6

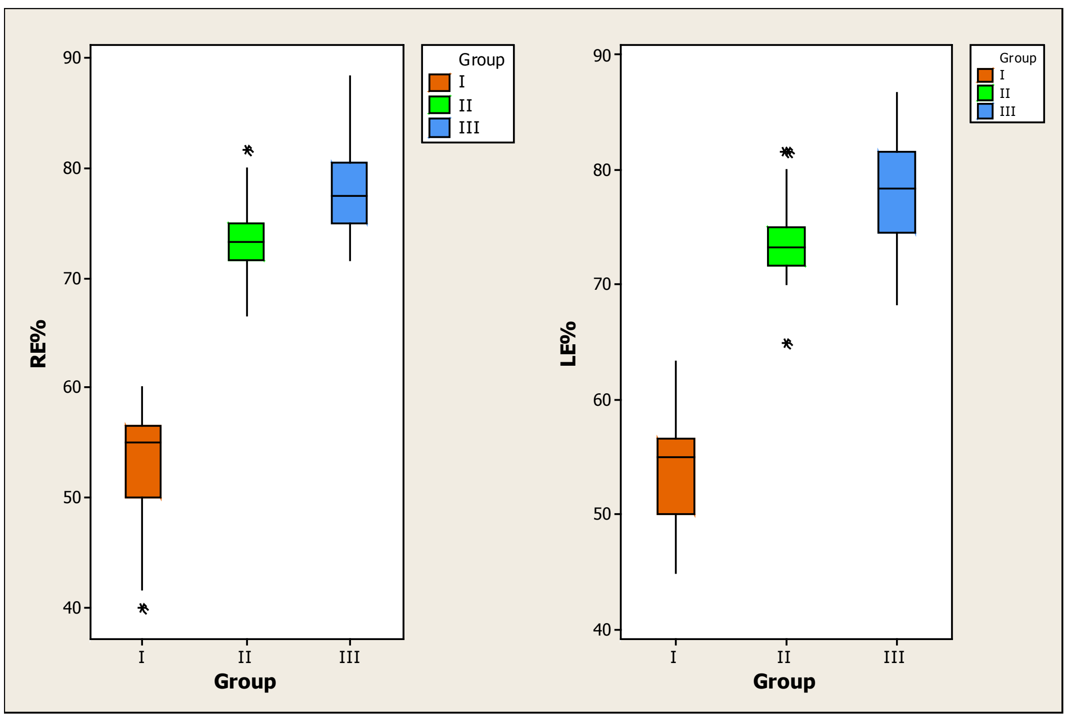

Figure 4. Box-plots for the percentage correct identification measure (%) for the right and left ears of Groups I, II, and III.

The mean percentage correct identification for the three groups was, however, significantly different ($F_{2,88}$ = 392.3; p = 0.000), which was not a predicted outcome in this study. Group III showed higher mean percentage correct identification scores than did Group II (t_{88} =4.46; p = 0.000) and Group I (t_{88} =26.3; p = 0.000) and Group II showed a significantly higher mean percentage correct identification than did Group I (t_{88} =21.5; p = 0.000). Here again, a similar pattern of results to that noted for the A.th. measure was observed for this measure; i.e., despite the fact that all three groups showed statistically significant differences in their percentage correct identification measures, a review of the data presented in Figure 4 shows that the performance of Group II was much more similar to the performance of Group III than to the results observed for Group I. As can be seen in Table 2, the mean percentage correct identification measures of Group II were closer to the mean values of Group III than they were to those observed for Group I, whose mean percentage correct identification scores fell slightly above 50% for each ear. As observed for the A.th. measure, the same rule applies for the percentage correct identification index; i.e., when there is little variation in the variable analyzed, small differences in the results can account for statistically significant differences between groups.

From a clinical perspective, as will be discussed in greater detail later in this chapter, the differences in performances on both GIN© test measures between Group II and Group III would not typically be considered clinically significant since both groups would have performed for the most part within the normal range for these measures based upon existing clinical norms. However, this was not the case for Group I where the performance of the majority of the participants fell outside of the range of normal performance; thus, suggesting that there were obvious and potentially diagnostically significant differences from a clinical assessment perspective between Group I and both Groups II and III.

Phonological Awareness Performance Comparisons Between Groups

Descriptive statistics for the phonological awareness subtests and for the composite score for Groups I, II, and III on the *Perfil de Habilidades Fonológicas* test are presented in Table 3 and Figures 5 and 6. A review of these data revealed that with the exception of the articulatory image task, Group III obtained higher mean scores than did Groups I and II for all subtest measures as well as for the composite score measure. Group I showed the lowest mean scores for all measures, with the exception of the analysis and articulatory image tasks, and Group II had an intermediate level of performance on all of the test measures, with the exception of the analysis and articulatory image subtests. On the latter subtest, the mean performance of Group II was equal to that of Group I.

As it was a requirement for group membership and although individuals participating in Group II were diagnosed with dyslexia, their performances fell within the normal range on the *Perfil de Habilidades Fonológicas* test as measured by the composite score. However, in spite of this requirement some differences were noted between the performance of this group and that of the of the typically developing readers.

Table 3. Descriptive statistics for nine phonological awareness subtests and the composite score on the *Perfil de Habilidades Fonológicas* for Groups I, II, and III.

Test Measures (number of items)	Group	N	Mean	Std. Dev.	Minimum	Median	Maximum
Analysis (16)	I	31	15.4	0.8	14	16	16
	II	30	14.3	1.4	12	14	16
	III	30	16.0	0.0	16	16	16
Blending (8)	I	31	3.4	0.5	3	3	4
	II	30	4.6	0.9	4	4	6
	III	30	7.6	0.7	5	8	8
Segmentation (12)	I	31	7.9	2.1	5	8	11
	II	30	9.5	0.6	8	10	10
	III	30	11.8	0.7	9	12	12
Deletion (8)	I	31	3.7	0.8	3	3	5
	II	30	6.0	1.1	4	6	8
	III	30	8.0	0.0	8	8	8
Substitution (4)	I	31	3.3	0.6	2	3	4
	II	30	3.8	0.4	3	4	4
	III	30	4.0	0.2	3	4	4
Rhyme Reception (8)	I	31	6.6	1.1	4	6	8
	II	30	6.9	1.3	4	8	8
	III	30	7.9	0.7	4	8	8
Rhyme Sequence (8)	I	31	3.3	1.0	2	4	4
	II	30	4.2	0.6	4	4	6
	III	30	6.5	1.5	2	6	8
Syllable Reversal (4)	I	31	2.0	0.0	2	2	2
	II	30	3.5	0.5	3	3	4
	III	30	3.6	0.7	2	4	4
Articulatory Image (8)	I	31	8.0	0.0	8	8	8
	II	30	8.0	0.0	8	8	8
	III	30	7.7	1.2	2	8	8
Composite score (76)	I	31	53.7	2.1	50	53	56
	II	30	60.6	1.8	58	60	64
	III	30	72.8	3.4	64	74	76

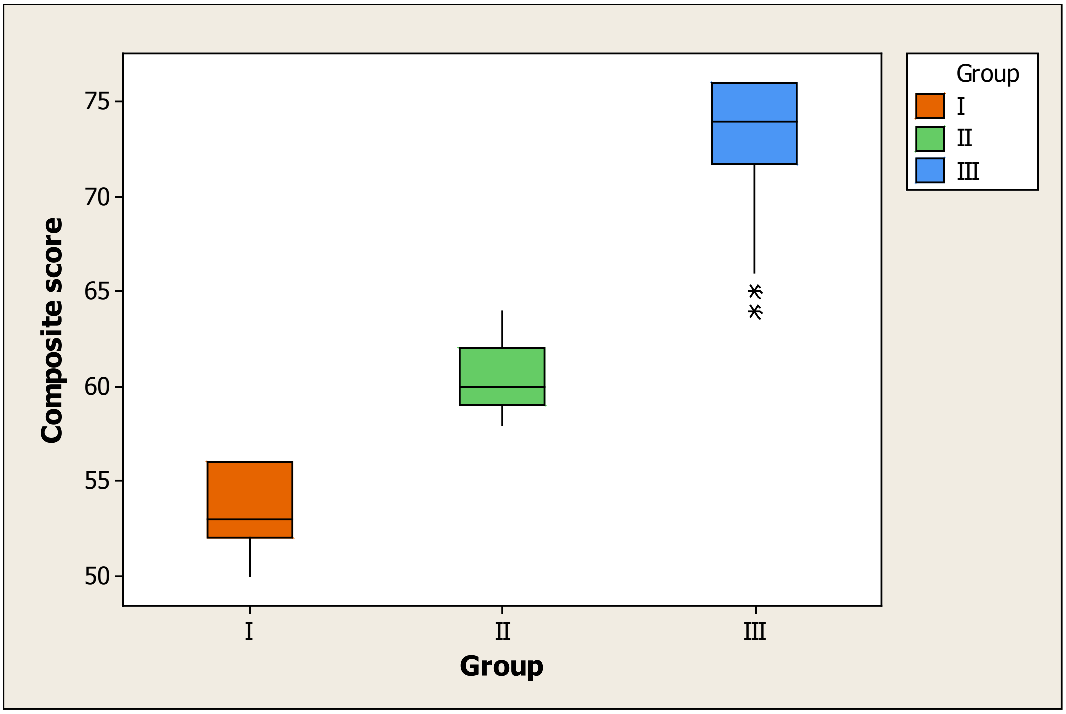

Figure 5. Box-plot for the composite score on the *Perfil de Habilidades Fonológicas* test for Groups I, II, and III.

An inspection of the data included in Table 3 revealed the lowest mean composite score for Group I (53.7%), the highest mean composite score for Group III (72.6%), and an intermediate mean score (60.6%) for Group II, while an inspection of the box plots presented in Figure 5 revealed no overlap in the distributions of composite scores on the *Perfil de Habilidades Fonológicas* test for Groups I and II or Groups I and III and minimal overlap in the distributions for scores for Groups II and III.

Correlations Between GIN© Test Measures and Phonological Awareness Measures

Spearman's correlation coefficients were obtained for each subtest of the *Perfil de Habilidades Fonológicas* test and the GIN© test measures (Table 4).

Table 4. Spearman's correlation coefficients between performance on the subtests of the *Perfil de Habilidades Fonológicas* and the GIN© test measures.

Subtest		GIN Threshold	GIN %
Analysis	Correlation Coefficient	-0.15	0.20
	p value	0.154	0.056
Blending	Correlation Coefficient	-0.79	0.76
	p value	0.000	0.000
Segmentation	Correlation Coefficient	-0.67	0.66
	p value	0.000	0.000
Deletion	Correlation Coefficient	-0.79	0.80
	p value	0.000	0.000
Substitution	Correlation Coefficient	-0.45	0.47
	p value	0.000	0.000
Rhyme Reception	Correlation Coefficient	-0.51	0.42
	p value	0.000	0.000
Rhyme Sequence	Correlation Coefficient	-0.65	0.67
	p value	0.000	0.000
Syllable Reversal	Correlation Coefficient	-0.70	0.71
	p value	0.000	0.000
Articulatory Image	Correlation Coefficient	0.17	-0.20
	p value	0.108	0.063

Only the articulatory image (coefficient = 0.17, p = 0.108 for the A.th. measure; coefficient = -0.20, p = 0.063 for the percent correct identification measure) and analysis (coefficient = -0.15, p = 0.154 and coefficient = 0.20, p = 0.056 for the for the A.th. and percent correct identification measures, respectively) subtest measures failed to show a significant correlation with either of the GIN© test indices. The remaining phonological tasks presented negative correlations with the A.th. measure; i.e., the higher the score on the phonological processing task, the shorter the A.th. measure.

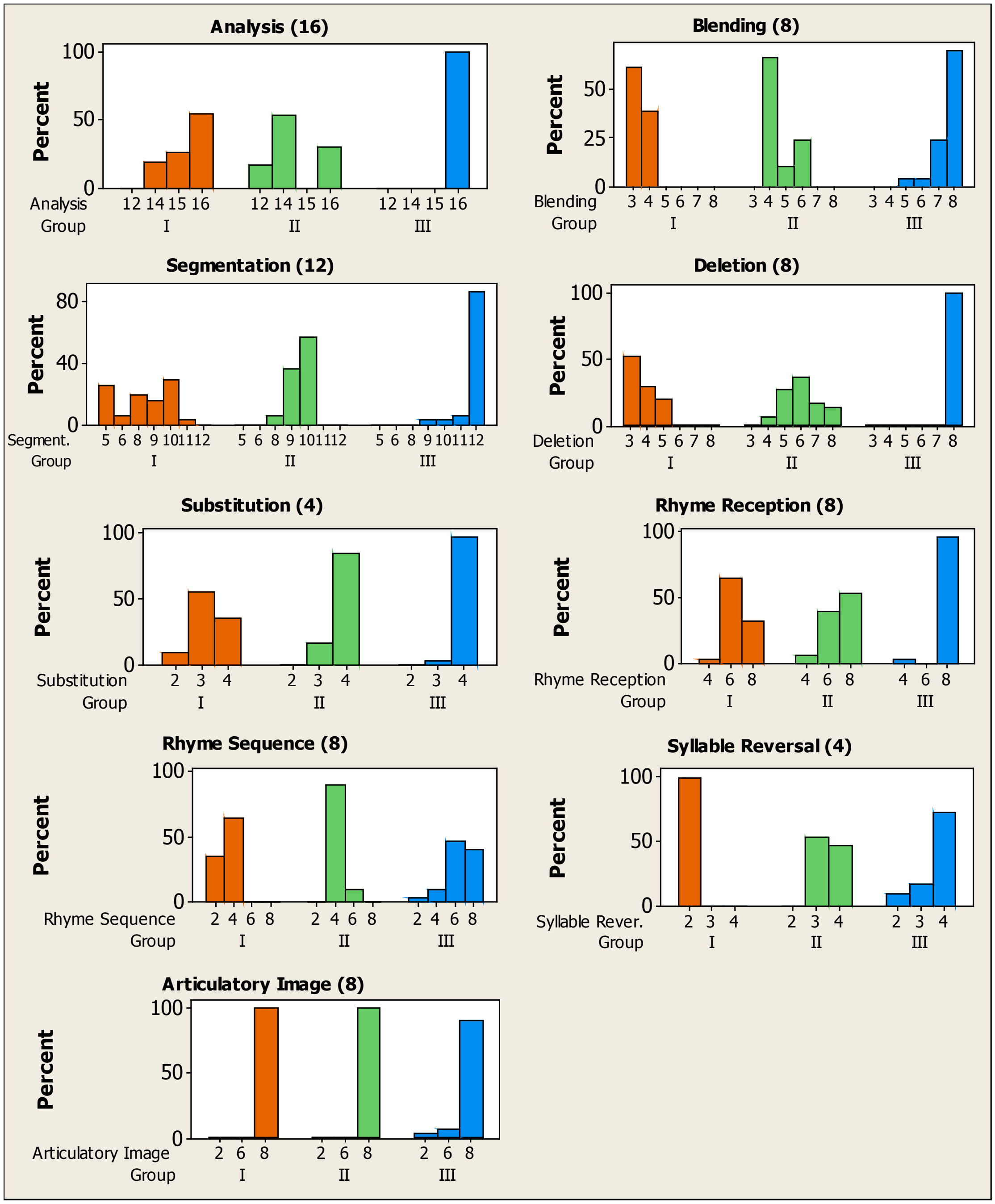

Figure 6. Bar charts of the distribution of correct responses for each subtest of the *Perfil de Habilidades Fonológicas* test for Groups I, II, and III.

For the percent correct identification response, a positive correlation was observed; i.e., the better the performance on the phonological processing task, the higher the percent correct identification score on the GIN© test. Overall, the highest correlations were noted for the deletion and blending subtests with both GIN© test measures, A.th. (coefficient = - 0.79; p = 0.000, for both tasks) and percent correct identification (coefficient = 0.80; p = 0.000 for deletion and coefficient = 0.76; p = 0.000 for blending).

Discriminant Analysis

Discriminant analysis was computed in the present study to determine a function, based on both GIN© test indices, which would discriminate among the three groups, Groups I, II and III. Since there were no differences between RE and LE performances for both GIN© test measures, the formulation of the discriminant analysis used values of both ears. The results of the discriminant analysis are presented in Table 5 and Figure 7. The discriminant function for the GIN© test measures in the present study yielded 82.4% of correct estimates, which indicates a great capacity of this test to discriminate among the three groups participating in this study.

Table 5. Discriminant function coefficients and percentages of correct estimates for Groups I, II and III.

	Groups			
	I	II	III	General
Constant	-351.86	-419.19	-438.5	
A.th.	32.46	32.56	32.68	
Percent(%)	8.15	9.2	9.45	
% correct estimates	100.0%	63.3%	83.3%	82.4%

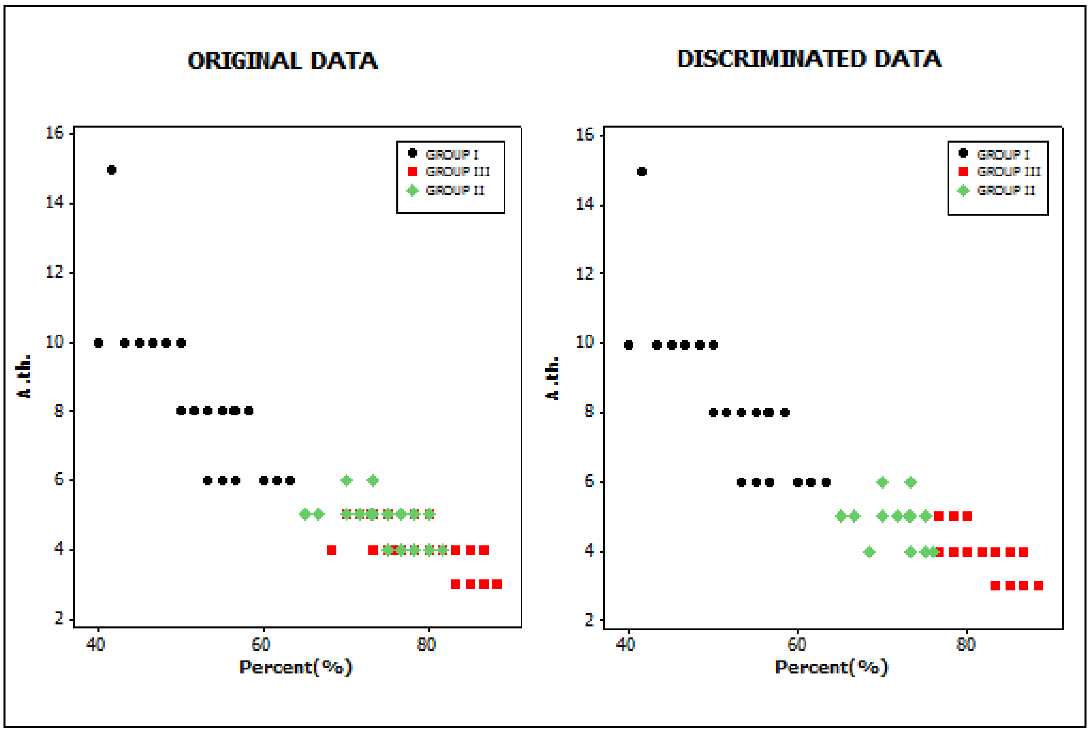

Figure 7. Original and discriminated group distributions for Groups I, II, and III.

Cut-off Values to Determine Normal and Abnormal Performance for the A.th. and Percentage Correct Responses Measures

A standard approach to determining the cut-off criterion between normal and abnormal performance for clinical application is to add two standard deviations to the mean performance of the normal participants, as presented in Figure 8 and Figure 9.

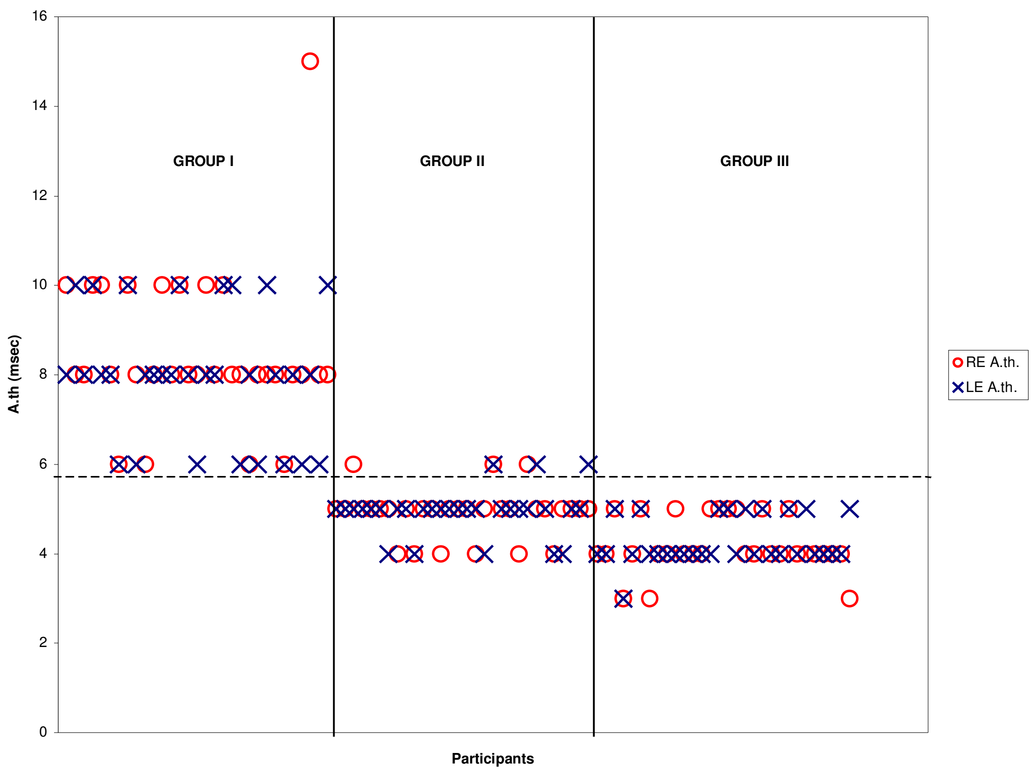

Figure 8. Individual data points for each participant as a function of ear for Groups I, II, and III. The dotted line represents the cut-off value using a two standard deviation criterion for the A.th. measure.

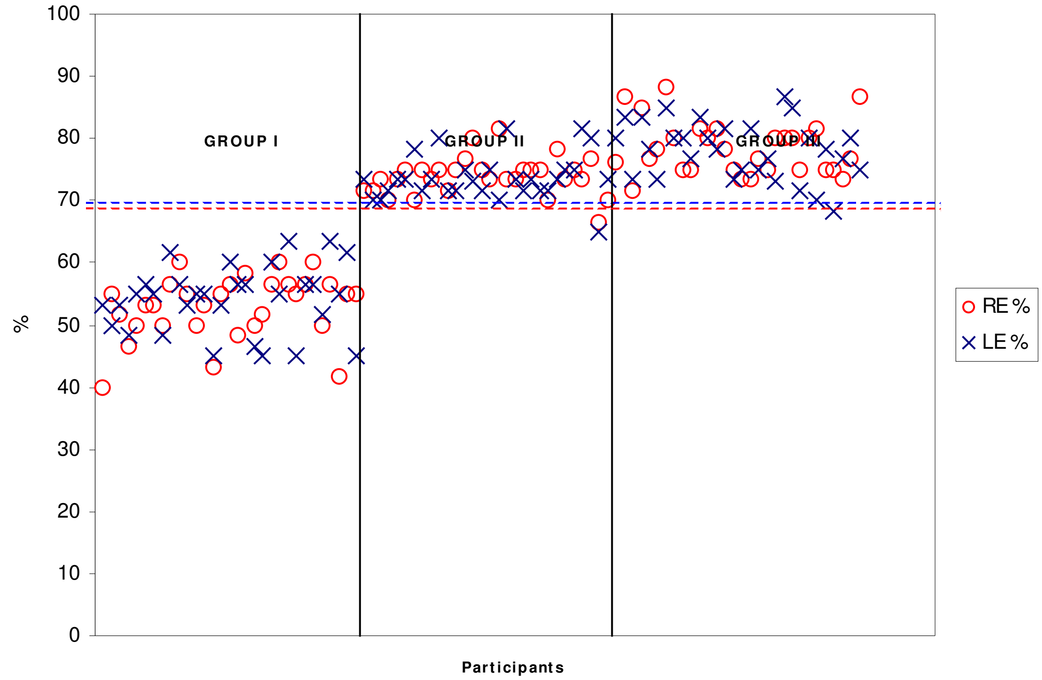

Figure 9. Individual data points for each participant as a function of ear for Groups I, II, and III. The dotted lines represent the cut-off values using a two standard deviation criterion for the percentage correct identification measure. The red line represents the cut-off value for the RE and the blue line represents the cut-off value for the LE.

Applying this approach to the present investigation, the cut-off for normal performance for the A.th. measure would be 5.3 msec for the LE and 5.4 msec for the RE. In other words, individuals who showed A.th. indices above this value would have failed the test. Since the gap durations used in the GIN© test do not include intervals of less than 1 msec, a performance equal to or above 6 msec therefore was considered to be abnormal. Applying this criterion to the sample, it is interesting to note that all participants (100%) from Group I would have failed the test in both ears, only 5 individuals (16%) from Group II would have failed the GIN© test in at least one ear, and all participants (0%) from Group III would have passed the test in both ears. In regard to the percent correct response measure, the cut-off for normal performance would be 68.7% for the LE and 69.7% for the RE. Applying these criteria to the sample, all participants from Group I (100%), only 1 individual (3.3%) from Group II and 1 (3.3%) from Group III would have failed the test in the LE. For the RE, all participants (100%) from Group I, 1 individual (3.3%) from Group II, and none of the participants from Group III (0%) would have failed the test.

It is often a common practice to combine clinical indices in an attempt to improve upon the efficiency of a test. In the present study if either an abnormal A.th. or an abnormal total correct response measure was employed as the diagnostic index of abnormality, all participants (100%) from Group I, 6 (20%) individuals from Group II, and none (0%) from Group III would have failed the GIN© test. On the other hand, if the cut-off criteria between normal and abnormal performance were established based on the GIN© test norms published for adults (Musiek et al, 2005), as well as for children (based upon a recent study with a small sample size of only 10 children per age group, Shinn et al., in press); that is 8 msec for the A.th. measure and 54% for the percent correct response index, 29 (96.6%) of the participants from Group I and none (0%) from Groups II and III would have failed the test in either ear if the criterion was the A.th. measure. If the percent of correct identification measure was used, 20 (66.6%) of the participants from Group I and none (0%) of the participants from Groups II and III would have failed the GIN© test in either ear using the adult norms. Normative values for the percent of correct identification index were not reported in the Shinn et al. (in press) study.

It is important to stress that although there were statistically significant differences among the three groups on both GIN© test mean measures, from a clinical perspective, the results obtained for individuals in Group II would have yielded a normal diagnostic index for the majority of the participants, while the performance of the majority of the individuals in Group I would have been clearly classified as abnormal for any of the cut-off criteria discussed above.

CHAPTER 5
DISCUSSION

The present study investigated the ability of the GIN© test (Musiek et al., 2005), an auditory temporal processing assessment test, as a procedure to differentiate a group of 8- to 9-year-old children with dyslexia and significant phonological awareness deficits from two different groups of children: one composed of normal reading peers and the other composed of children who had been diagnosed with dyslexia, but who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits as evidenced by normal performance on a composite score of phonological processing, but isolated deficits on one or more of the phonological processing subtests.

Approximate Threshold (A.th.) and Percent Correct Identification Comparisons Between Groups

Findings for both GIN© test measures, percent of correct identification and A.th., are discussed simultaneously as both indices showed the same pattern of results. This is somewhat expected since these measures are not totally independent of each other and are likely to covary, e.g., if the A.th. of an individual was 10 msec, it would mean that the individual identified a maximum of three of the six presentations of the 8 msec gaps (A.th. is determined by 4 out of 6 correct identifications) and most likely he/she correctly identified even fewer of the six presentations of the shorter gap durations, which ultimately would result in a low or reduced percentage of correct identifications of all of the gaps presented in the test.

In other words, the larger the A.th. measure, the lower the percentage of correct identification index would be, and vice versa.

Although all three groups performed significantly different from each other on both GIN© test measures from a purely statistical standpoint, a closer inspection of the data provided evidence that the performance of participants from Group II was much more similar to the performance of Group III than to the performance of Group I. This observation was supported by the clinical analyses conducted, which indicated that based upon standard clinical decision analytic procedures, the differences in performances on both GIN© test measures between Group II and Group III would not have been considered clinically significant since all individuals from Group III and the majority of individuals from Group II would have performed within the normal range. However, this was not the case for the majority of the participants in Group I, whose performance fell outside the range of normal performance; thus, their performance was significantly different both from a clinical and a statistical perspective from that of the other two groups. In other words, even though statistically significant differences were found among the performances of the three groups studied, resulting in an unexpected outcome for this study, from a clinical perspective, the null hypotheses can be rejected suggesting that the presence of phonological awareness difficulties is correlated with the presence of auditory temporal processing deficits as measured by GD thresholds and/or percentages of correct responses indices of the GIN© test.

The significant statistical difference found among the performances of the three groups studied can potentially be explained in terms of the correlation between phonological awareness difficulties and auditory temporal processing deficits. Even though participants from Group II showed composite scores within normal limits on the *Perfil de Habilidades Fonológicas* test, some of these children showed reduced performance on a small number of the phonological subtests. Further, an inspection of the individual data for Group II showed that the participants from this group who failed the GIN© test on either one or both indices as determined by the cut-off values obtained for the sample, all exhibited greater difficulties in two of the phonological subtests: blending and deletion. These tasks, not coincidently, showed the highest correlation indices with both GIN© test measures for all participants across all three groups. In other words, it is possible that these tasks are more dependant or more loaded on auditory temporal processing skills than the other measures included in the *Perfil de Habilidades Fonológicas* test; thus, explaining the abnormal performance of these individuals on the GIN© test.

The findings of the present investigation are consistent with results from other investigations that also reported links between auditory temporal processing deficits and phonological abilities in individuals with dyslexia (Talcott et al., 2000; Breznitz & Misra, 2003; Cohen-Mimran & Sapir, 2006; Boets et al., 2007; Boets et al., 2008). Boets and colleagues (2008) using causal path analysis suggested that dynamic auditory processing and phonological awareness skills influence each other reciprocally. This might explain the fact that, in the present investigation, participants with clear phonological deficits as measured by abnormal performance on the composite score of the phonological processing test administered also showed longer A.ths. and smaller percentages of correct identifications on the GIN© test in comparison to those individuals with dyslexia with no or only mild phonological deficits as evidenced by normal performance on the composite test score and either normal subtest measures or isolated deficits on one or more of the subtest measures.

Results of the present investigation also confirmed previous anatomical, electrophysiological, and behavioral findings that indicated that auditory temporal processing is a factor to be accounted for when studying dyslexia in both adults (Galaburda et al., 1985; Humphreys et al., 1990; Galaburda et al., 1994; Stein & McAnally, 1995; Protopapas et al., 1997; Edwards, 2000; Galaburda, 2002; Breznitiz & Misra, 2003; Giraud et al., 2005; Moisescu-Yiflach & Pratt, 2005; Petkov et al., 2005; Hoen et al., 2008) and children (Menell et al., 1999; Talcott et al, 1999; Breier et al., 2001; van Ingelghem et al., 2001; Rocheron et al., 2002; Hautus et al., 2003; Hood & Conlon, 2004; van Ingelghem et al., 2004; Montgomery et al., 2005; Putter-Katz et al., 2005; Cohen-Mimran, 2006; Cohen-Mimran & Sapir, 2006; Boets et al., 2007; King et al., 2007; Veuillet et al., 2007; Boets et al., 2008). The fact that not all participants with dyslexia showed an auditory temporal resolution deficit does not suggest that auditory temporal processing should be excluded as a potential cause of dyslexia for two reasons. First, results of the GIN© test were correlated with results of the phonological test, suggesting that auditory temporal deficits were related to phonological difficulties. Second, the current conceptualization of dyslexia based upon the available literature is that dyslexia is a complex disorder with several clinical manifestations potentially caused by multiple cognitive and perceptual factors (Pennington, 2006; Snowling, 2008), but that the presence of all of these perceptual and cognitive factors is not a necessary condition for its diagnosis. In other words, not all test scores within a multidisciplinary or intradisciplinary test battery will be low for all individuals with reading disabilities and performance will vary depending upon the contributing factors for dyslexia for each individual. In this line, it is not unexpected, as reported in the present study, that individuals with dyslexia would show not only different degrees of auditory temporal processing deficits, but also varying degrees of phonological difficulties.

Phonological Awareness Measures

In the present investigation, not all individuals with dyslexia showed a clear evidence of phonological awareness difficulties. Participants from Group I performed below expectations for their age on all tasks with the exception of the articulatory image and analysis subtests. Group II performed within normal limits as demonstrated by the composite score on the *Perfil de Habilidades Fonológicas*; however, some of the participants in this group showed isolated difficulties on specific subtests, such as blending and deletion. Unfortunately, one limitation of the *Perfil de Habilidades Fonológicas* is that the test offers only a few test items for each phonological ability which limits data comparison and more in depth analysis. On the other hand, since phonological processing difficulties are considered by many researchers as the core deficit underlying reading disability (Bradley & Bryant, 1978; Siegel, 1993; Snowling, Nation, Moxham, Gallagher, & Frith, 1997; Shaywitz, 1998), it is surprising that not all participants with dyslexia demonstrated phonological awareness deficits.

One explanation for this finding is that phonological awareness is just one aspect of phonological processing, which also can be assessed by other means such as verbal short-term memory evaluation (i.e., the ability to maintain phonological representations active), and verbal retrieval tasks (i.e., the ability to retrieve phonological forms of words from among others) (Snowling, 2000). Therefore, it is possible that the children with dyslexia who did not show obvious phonological awareness difficulties could have demonstrated deficits in other types of phonological processing skills.

A second possibility that has been reported in the literature is that the expression of phonological deficits in dyslexia might vary across different languages (Shaywitz, Moris, & Shaywitz, 2008). For example, it has been found that in languages with orthographies that are more consistent (i.e., they have consistent phonemic-letter linkages, such as in Brazilian Portuguese and Italian), children with dyslexia tend to demonstrate phonological deficits that are apparent only during their early reading instruction (Ziegler & Goswani, 2005), whereas in languages such as English, with more unpredictable letter-sounds mappings, deficits in phonological processing are noted early on and tend to persist throughout the school years (Shaywitz, Fletcher, Holahan, Shneider, Marchione, Stuebing, Francis, Pugh, & Shaywitz, 1999). Hence, children from Group II who did not demonstrate major phonological awareness deficits could have shown difficulties in earlier years and improved these skills during reading development. It is important to emphasize that participants from this group had an intermediate performance on the phonological test and did not show the same ability as normal developed reading peers. It is therefore possible that the children in this group may have had more severe deficits at an earlier age, but that with reading instruction the severity of deficits have been lessened. Further, the fact that individuals from Group I still demonstrated significant phonological awareness difficulties after the exposure to reading instruction in the schools might indicate that, as suggested by Boets and colleagues (2007), the presence of auditory deficits has the potential to aggravate phonological impairments in dyslexia and hampered their recovery.

Finally, the findings reported by Snowling (2008) are consistent with the results of the present investigation. Snowling suggested that phonological deficits are not necessary or sufficient to account for dyslexia, especially if reading disability is viewed as a continuously distributed dimension. Her results indicated that those individuals who fall at the lower end of the continuum are more likely to have poor phonology, but they are also more likely to have other cognitive or perceptual deficits as well.

The Feasibility of the GIN© Test as a Clinical Tool

Although there is a relatively long history of GD investigation, this procedure has not been used widely for clinical applications even though researchers have shown the procedure to be valuable in measuring temporal resolution abilities. The reason is that GD procedures were not feasible in a clinical setting was because they were very time-consuming, making them difficult to use within a test battery or with patients or children who could not tolerate long periods of testing (Musiek et al., 2005). The GIN© test was developed with the expressed purpose of providing a clinically feasible method of evaluating GD abilities in a variety of populations. The results of the present investigation are consistent with previous findings reported for the GIN© test regarding clinical feasibility and equivalent performance between ears.

The performance of the normal reading group, GROUP III, on the two measures of the GIN© test, A.th. and percent of correct identification was consistent with the values obtained in other studies with normal populations. The present study, which included a larger number of children in the 8- to 9-year-old range than earlier studies found mean A.ths. of 4.2 msec for the RE and 4.3 msec for the LE. These results were similar to the values reported for children (Chermak & Lee, 2005; Shinn et al., in press) and adults (Musiek et al., 2005; Sammeli & Schochat, 2008) in previous studies using the GIN© test. Only slight differences were found between the mean A.ths. reported in this study and the results obtained by Musiek and colleagues (2005), Chermak and Lee (2005), and Shinn and colleagues (in press), while the present results were essentially the same as those reported by Sammeli and Schochat (2008). This latter study and the present investigation found slightly shorter mean A.ths. (less than 1 msec shorter) on the GIN© test in comparison to the other three studies. Interestingly, Sammeli and Schochat (2008) and this study were both conducted in Brazil with Portuguese speaking populations and the other studies (Chermak & Lee, 2005; Musiek et al., 2005; Shinn et al., in press) were conducted in the United States with English speaking populations. The small but consistent differences between the A.th. results in these two groups of studies could be associated with small acoustical differences in the speech patterns of the two languages that signal phonetic differences.

A similar difference between GIN© test results was also noted for the percent of correct identification index among the three studies that reported this measure; i.e., the present investigation and Sammeli and Schochat (2008) found mean percentages of 78.20% and 78.89%, respectively, and Musiek and colleagues (2005) reported mean percent correct identification on the order of 70.25%. Unfortunately, the other two studies that examined GIN© test performance (Chermak & Lee, 2005; Shinn et al., in press) did not report their results for this measure, which may have been because most of the literature on GD paradigms has focused on the determination of a GD threshold and not on the total number of correctly identified gaps. In addition, in one of these studies (Shinn et al., in press), the authors suggested that the percent of correct identification measure is regarded to yield poorer sensitivity and specificity than the A.th. measure of the GIN© test. This argument, however, was not supported by the results of the present study. Specifically, this investigation found that both indices covaried with each other and that individuals who performed below normal limits on one measure tended to perform outside of the range of normal on the second measure and vice versa.

Although differences between the performances of adults and children on many measures of auditory processing abilities have been reported in the literature (Irwin et al., 1985; Schneider et al., 1989;

Wightman et al., 1989; Hall III & Grose, 1994; Schochat & Musiek, 2006), the developmental time course of temporal resolution, more specifically of GD ability, has not been clearly established. In the present study, the mean A.ths. obtained for the normally developing participants in Group III were similar to those reported by both Chermak and Lee (2005) and Shinn and colleagues (in press) for children and to those reported by Musiek and colleagues (2005) and by Sammeli and Schochat (2008) for adults, suggesting early maturation of the GD ability in children. Thus, unlike what has been observed for the majority of central auditory processing abilities, temporal resolution, as measured by the GIN© test, appears to have reached adult stages of development by 7 years of age (Shinn et al., in press). These results, however, are contradictory to those of several other investigations where the results indicated that temporal resolution as assessed by GD paradigms did not reach adult levels until the age of 10 years or later (Elliott & Katz, 1980; Irwin et al., 1985; Grose et al., 1993; Werner & Marean, 1996). These highly contrasting results can be explained in terms of the variability of stimuli employed and the types of responses required by the tasks used to assess GD ability. For example, when white noise stimuli were presented at above threshold levels, as was the case in the GIN© test studies reported, minimal detectable gaps were reported to be on the order of a few msec (Plomp, 1964; Fitzgibbons, 1983; Shailer & Moore, 1983; Moore, Peters, & Glasberg, 1993). However, when low-frequency stimuli were used, GD thresholds were longer (Wightman et al., 1989; Grose et al., 1993). Also, it has been suggested that since the motor response required by the GIN© test is potentially less cognitively demanding than the two-alternative forced-choice tasks or adaptive trials employed by several studies (e.g., Irwin et al., 1985; Wightman et al., 1989; Werner & Marean, 1996), that the use of a motor response can minimize potential cognitive confounds during the test and improve performance (Chermak & Lee, 2005).

No differences between RE and LE performances were observed for all groups studied in the present investigation, suggesting that both GIN© test measures (A.th. and the percent of correct identification) were similar for both ears. These results are consistent with findings reported in the literature for GIN© test performance in both children and adults (Chermak & Lee, 2005; Musiek et al., 2005; Sammeli & Schochat, 2008; Shinn et al., in press), as well as with several other studies that employed other GD paradigms (Efron, Yund, Nichols, & Crandall, 1985; Baker, Jayewardene, Sayle, & Saeed, 2008; Carmichael, Hall, & Phillips, 2008). Since there were no differences in performances between ears in any of the studies reviewed, including the present investigation, the possibility exists that accurate diagnosis of a temporal resolution deficit could be made if testing with the GIN© test is done either in the soundfield, diotically under headphones, or monaurally only in one ear. Such an approach to assessing temporal resolution ability can reduce testing time while still maintaining diagnostic efficacy and efficiency, which could potentially be a consideration when evaluating patients or children who cannot tolerate long periods of testing.

Regarding the classification of the GIN© test as one of the two types of GD test procedures, even though this test has characteristics of both within- and between-channel GD paradigms (Phillips et al., 1997; He et al., 1999) and may even represent a new GD paradigm (Hurley & Fulton, 2007), the findings in previous studies (Chermak & Lee, 2005; Musiek et al., 2005; Sammeli & Schochat, 2008; Shinn et al., in press) and in the present investigation are more consistent with the within-channel GD thresholds reported in the literature than with the between-channel GD thresholds. For instance, Boehnke and Phillips (1999) found that for the within-channel condition, GD thresholds varied between 2 and 6 msec, whereas for the between-channel paradigm GD thresholds ranged between 10 and 50 msec. Phillips and Smith (2004) reported GD thresholds of 5 to 8 msec for the within-channel paradigm and of 28.7 msec for the between-channel condition in normal adult listeners. Additional research is needed to determine to which category, within-channel or between-channel, the GIN© test belongs to or if it really represents a new GD paradigm as has been suggested by Hurley and Fulton (2007).

GIN© Test's Discriminant Analysis Result and Cut-off Values for Normal and Abnormal Performance

According to the results of the discriminant analysis the GIN© test measures were very powerful in discriminating among the three groups participating in the present study. In other words, the GIN© test measures efficiently discriminated participants from the three groups with a correct estimate index of 82.4%. This index shows that for the qualifications of the population studied in this investigation the GIN© test was very efficient in accurately classifying individuals in each of the three groups: children with dyslexia and significant phonological awareness deficits, children with normal reading skills and children who had been diagnosed with dyslexia, but who did not show evidence of phonological awareness difficulties or who demonstrated only mild phonological processing deficits.

The fact that the GIN© test was efficient in identifying auditory temporal resolution difficulties among children who participated in this study suggests that this test should be used along with other perceptual and cognitive evaluation procedures when assessing children with reading and writing difficulties. Although normative values for the GIN© test are still limited, results of the present investigation suggested 6 msec for the A.th. and 69.2% for the percent of correct identification measure as cut-off values for normal and abnormal performance. These values are slightly different from the values reported by Musiek and colleagues (2005) and Shinn and colleagues (in press) who suggested cut-offs of 8 msec for the A.th. index and 54% for the percentage of correct identification measure. Additional normative studies for the GIN© test using larger samples are needed to definitively establish cut-off values for normal and abnormal performance.

Limitations of the Current Research Investigation

One limitation of the present investigation was the use of the *Perfil de Habilidades Fonológicas* test to assess phonological awareness abilities. This test had only few test trials for each phonological awareness ability assessed, which limited the analysis of the results in this area. Unfortunately, at the time of the data collection there were no other commercial tests of phonological awareness available in Brazil. Another limitation was that this study did not use additional assessment procedures to test different aspects of phonological processing and language skills, which would have characterized in more detail the language abilities of the populations studied and provided more insights regarding the relationship between auditory temporal processing and phonological processing in dyslexia. A final limitation was the subject selection criteria employed for Group II. If the subject inclusion criteria for Group II could have been made more stringent so that the subject selection criteria for inclusion in this group required normal performance on all subtest measures as well as the composite score measure of the *Perfil de Habilidades Fonológicas* test, it is likely that the results would have shown a more straightforward link between auditory temporal processing and phonological awareness abilities in dyslexia.

Future Research Needs

A number of important future directions are proposed in the present investigation. First, as was suggested in the literature review, phonological processing deficits in children at-risk for dyslexia might be present early in childhood but there is no study evaluating these children for auditory temporal processing. Gathering these data would enlighten what is currently known and disclose new information regarding different clinical manifestations of dyslexia, which could potentially lead to the earlier identification of this disability.

Second, since the GIN© test is a relatively new assessment tool additional clinical investigations of its test characteristics and performance are needed, Specifically, additional normative studies with larger sample populations are needed as the available data for the GIN© test has been obtained with relatively small sample populations (e.g., in the Shinn et al. study (in press) only 10 subjects per age group were included in the sample population). In addition, different clinical populations should be studied to provide more information regarding the sensitivity and specificity of this test. Finally, additional studies should be conducted in different language speaking populations as the results of the present investigation and of other studies (Chermak & Lee, 2005; Musiek et al., 2005; Sammeli & Schochat, 2008; Shinn et al., in press) suggest that slight differences in the GIN© test measures may arise based on language differences.

Conclusions

Dyslexia is a heterogeneous disorder characterized by several clinical manifestations and behavioral symptoms. The prevalence and the contribution of each of these manifestations and symptoms are still largely unknown and their relationship with each other remains undetermined. As is the case in most developmental disorders, the constellations of symptoms in dyslexia may change with maturation and/or environmental and intervention effects. For these reasons, the only way to truly help individuals who struggle to read and write is to assess all of the sensory and cognitive skills that may impact language acquisition and reading ability so that intervention planning can focus on facilitating and/or remediating the auditory, linguistic, and cognitive processes or skills that are needed for normal oral and written language abilities to be realized.

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