12-9-2011 12:00 AM

Acoustic Signal Encoding in Children with Auditory Processing Disorders

Chris M. Allan, *The University of Western Ontario*

Supervisor: Dr. Prudence Allen, *The University of Western Ontario*
A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Health and Rehabilitation Sciences

ACOUSTIC SIGNAL ENCODING IN CHILDREN WITH AUDITORY PROCESSING DISORDERS

(Spine title: Acoustic Signal Encoding in Clinical Populations)

(Thesis format: Monograph)

by

Chris Marie Allan

Graduate Program in Health and Rehabilitation Sciences
(Hearing Science Field)

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

THE UNIVERSITY OF WESTERN ONTARIO
School of Graduate and Postdoctoral Studies

CERTIFICATE OF EXAMINATION

Supervisor

____
Dr. Prudence Allen

Supervisory Committee

____
Dr. Meg Cheesman

____
Dr. Vijay Parsa

Examiners

____
Dr. Tony Leroux

____
Dr. Debra Jared

____
Dr. Susan Stanton

____
Dr. Meg Cheesman

The thesis by

Chris Marie Allan

entitled:

ACOUSTIC SIGNAL ENCODING IN CHILDREN WITH AUDITORY PROCESSING DISORDERS

is accepted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

____
Date

____
Chair of the Thesis Examination Board

Abstract

Auditory perception, as measured through the ability to resolve and discriminate acoustic signal features, has been shown to be a problem for some children with learning, language, reading, or attention disorders. Evaluation of discrimination abilities, as part of an auditory processing test battery, has been recommended but few commercial tools are available for the audiologist to accomplish this task. The investigation of signal feature discrimination or resolution has occurred in the laboratory, but few studies have been conducted with children at risk for an auditory processing disorder (APD). The purpose of this project was to investigate signal encoding abilities in children suspected of having APD.

School-aged children, part of a clinical population referred for auditory processing evaluation, participated in the project. Children underwent a clinical auditory processing assessment and were designated into APD or non-APD groups. To assess signal encoding abilities, an adaptive procedure with feedback was combined with a three alternative forced choice task and presented with graphics in a game-like format. A series of five studies was designed to represent spectral, level, and temporal features of sound and allow for a sampling of the encoding abilities of the clinical population. The series included evaluation of frequency resolution, frequency discrimination, intensity discrimination, temporal resolution and temporal integration.

Results demonstrated that some children (APD and non-APD) in the clinical population have difficulty accurately and efficiently encoding acoustic signal features. Poor performance varied on an individual and group basis across signal encoding tasks but most listeners demonstrated difficulty with spectral and temporal encoding. Elevated and outlying thresholds were not restricted to the APD group although the largest numbers of poor performers were those in that group. In addition to the threshold values, trial-by-trial data provided qualitative information about the nature of the poor performance and assisted in differentiating poor signal encoders from children who were inattentive.

It was concluded that the clinical assessment of signal feature encoding can contribute to the accurate identification of children with APD and should be included in a clinical test battery. The psychoacoustic task can successfully assess signal encoding in the clinical setting.

Keywords

Auditory processing disorder, (central) auditory processing, psychoacoustics, auditory signal feature encoding, discrimination, temporal processing, spectral processing, children

Acknowledgments

I would like to thank all the children, and their families, who participated in this project. I am grateful not only for the time they committed to the project but also for the opportunity I had to work with them.

I extend my utmost gratitude to my supervisor, Dr. Prudence Allen, for her guidance, support, insight and encouragement during my doctoral study journey. Dr. Allen has been an inspiration, a valued collaborator, and a mentor. I will always treasure our friendship. I also express my appreciation to the members of my advisory committee, Dr. Meg Cheesman and Dr. Vijay Parsa for their thoughtful contributions to my research. I extend my sincere thanks to Steve Beaulac and David Grainger for their expertise, advice, guidance, and attention through the technical challenges of my research. A special thank-you goes to Karen Ballem for editorial advice.

It would not have been possible for me to complete this work without the love, prayers, and support of family and friends. I would like to thank my family and friends who, in a variety of ways, encouraged me through this endeavour. My husband, Gary, and children, Keegan and Mitchell, along with my extended family have been my strongest supporters and have shown both love and patience through the challenge of my doctoral studies. Thanks to Keegan for never allowing "quitter talk" and to Mitchell, for being an example of perseverance. Thanks to my parents and sister who have been unfailing in their support of all my professional and academic pursuits. I also extend my thanks to friends and colleagues that offered encouragement through the good times and the bad. I deeply appreciate your understanding and faith. Finally, I would like to recognize and thank my classmates, Wenonah Campbell, Christine Guptill, and Flora Stephenson, for always being available when most needed. Thank you for sharing with me your thoughts and perspectives on life, career, and academics. I will always cherish our friendship.

Dedication

Revelation 4:11

Isaiah 40:8

Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1

1 Auditory perception and processing

The world is rich with complex auditory signals that include speech, music and a cacophony of environmental sounds. Of these sounds, speech is the primary means of communication and the conduit for learning in the traditional educational system. The importance of speech cannot be understated when considering its relevance to daily communication and learning. To understand auditory information, including speech, an individual requires not only normal hearing sensitivity but also good perception, an ability that changes as a child matures. Sensation requires perception in order for meaning to be assigned to the stimulus and in turn, for the perceptions to be learned.

Perceptual learning begins with exposure to physical stimuli. For the auditory system, the stimuli are the sounds that we hear. With repeated exposure to sound, specific signals become more familiar and learning takes place. Goldstone (1998, 2003) explained that perception occurs early in information processing and that perceptions develop over time. Such learning improves responsiveness to stimuli in the environment. Goldstone provided insight into the way we perceive, learn to perceive, and ultimately associate sensation with meaning. Mechanisms that come into play include attentional weighting, stimulus imprinting, differentiation, and unitization. Through these perceptual mechanisms the efficiency of stimulus processing is developed. They allow for the fast and accurate recognition of stimuli.

Goldstone (1998) explained that children gain experience in their environment as they interact with their surroundings and the physical properties of the world, including the sounds that they hear. As this experience grows, children begin to make associations between sound and meaning. The more frequently sounds are heard the more likely they are to be recognized. This occurs in part through the enhancement of neural connections in the central auditory nervous system (stimulus imprinting). Children can begin to focus attention towards salient features or dimensions of sounds that are important for identification and classification, and attend less to those that are irrelevant (attentional weighting). As groups of sounds occur repeatedly together, the individual elements become associated (begin to be recognized as a whole) so that detection of one part of the unit triggers recognition of the whole, even in degraded conditions (unitization). This significantly speeds the processing of auditory information. As signals are better learned, finer detail can be perceived (differentiation) which seems to improve discrimination abilities.

It is with the presence of normal hearing sensitivity and efficient processes of perceptual learning that children are able to become good auditory processors and listeners, understand oral communication, and learn. Any degree of hearing loss can, and typically does, have a negative impact on auditory related abilities (Holstrum, Biernath, McKay, & Ross, 2009; Ross, Gaffney, Green, & Holstrum, 2008; Yoshinaga-Itano, Johnson, Carpenter, & Brown, 2008). An interruption or interference in the perceptual learning process can also have a negative impact on auditory abilities (Moore, Hogan, Kacelnik, Parsons, Rose, & King, 2001). When sensation or perception is compromised, the ability to hear may be insufficient for the appropriate development of speech-language skills (Moore, Amitay, & Hawkey, 2003). Academic success as defined by performance in a typical classroom setting for which signals may be unfamiliar or unclear can also be compromised (Bamiou & Luxon, 2008; Carneol, 2008; Levy & Parkin, 2003). Difficulties with auditory tasks and listening, despite the presence of normal hearing sensitivity, are known as auditory processing disorders.

1.1 Auditory Processing Disorder

Not all children possess and develop good auditory processing abilities. Many have difficulty with encoding sound features and associating meaning to them. Some have difficulty with detection of sounds, although the co-morbidity between deficits in detection (peripheral hearing loss) and processing disorders has not been extensively researched (Jerger, 2007; Jutras & Gagne, 1999; Koravand, Jutras, & Roumy, 2010). The presence of hearing loss or an auditory processing disorder can interfere with learning in a traditional educational system which relies on oral communication (Palmer, 1997).

Children with hearing loss are often identified during infancy because of universal hearing screening programs. This results in early intervention that reduces the negative impact of the hearing loss on the child's learning, speech-language, and social development (Fitzpatrick & Durieux-Smith, 2011; Moeller, 2000; Wolff, Hommerich, Riemsma, Antes, Lange & Kleijnen, 2009). Elementary school integration and academic performance may also be influenced through early intervention (McCann, Worsfold, Law, Mullee, Petrou, Stevenson, Yuen & Kennedy, 2009; Verhaert, Willems, Van Kerschaver, & Desloovere, 2008). Unfortunately, young children with auditory processing problems are frequently identified after school entry, when they have already begun to experience academic failure. Identification of and intervention for perceptual problems occurs at a much later age than for losses of sensitivity due to factors such as the complex nature of the auditory nervous system and its relatively long developmental trajectory for auditory abilities. Extensive variability of performance in typically developing children on auditory perceptual tasks and the wide range of important auditory processing abilities preclude the feasibility of a single test for identification. These issues coupled with diverse presentation of the disorder, are key reasons for late identification of auditory processing disorder in children.

Children experiencing a developmental delay or disorder in their auditory processing and perceptual abilities are more likely than typically developing children to experience problems in a classroom setting. Learning to read, which typically occurs after school entry, places the most significant demands on auditory processing. Prior to that, children often find themselves in homes where oral communication with parents and other children is conducted at relatively close distances and vocabulary is relatively familiar, requiring less focus on the acoustics. Such a favorable communication environment makes signals more audible, improves clarity and improves signal-to-noise ratios. In school classrooms, auditory demands increase, noise levels may be higher (Bradley, 2005; Howard, Munro & Plack, 2010; Klatte & Hellbruck, 2010) and much of the information presented by the teacher is novel. Auditory information that has never before been encountered by children requires additional resources to be understood (Goldstone, 1998, 2003). Automatic recognition of signals, as might occur when sound combinations have already triggered unitization, is less available with novel information. The ability to differentiate signals as novel, attend to the relevant features, and process the acoustic information for understanding and future reference becomes a constant demand in the classroom setting, where learning new information is an ongoing process for children.

Poor auditory perception can have a negative impact on academic success and the ability to listen and learn in a typical classroom (Hutchinson & Mauer, 1998). Increased stress from demands on auditory skills in the classroom may lead to poor academic performance and/or behaviour problems. It is through observed behaviours, often associated with difficulties in academic achievement, that the possibility of an auditory problem is initially suspected (Bamiou, Musiek, & Luxon, 2001; Bench, 1998). A child with an auditory processing problem tends to show typical behaviours such as frequent requests for the repetition of auditory information and frequent misunderstanding of auditory information especially when it is degraded or when the listening conditions are compromised (Yalcinkaya & Keith, 2008). They may be more distractible, have a slower processing time for auditory information, and show difficulty learning through the auditory modality (Keith, 1999; Willeford & Burleigh, 1985, Chapter 3). Children with auditory processing difficulties may also show a short attention span, be easily distracted, become frustrated when learning new information, have a poor ability to organize information, have trouble with memory, appear to daydream, be slow to respond to questions or instructions, display disruptive behaviour, become isolated, give up easily and fail to complete tasks that are difficult (Friel-Patti, 1999; Keith, 2004; Sahli, 2009). It is most often these behaviours and the beginning of academic difficulties that lead to a hearing test and evaluation of auditory processing abilities (Keith, 2004; Willeford, 1985).

The extent to which an auditory processing disorder and other associated behaviours are expressed or impact the ability to function in a regular classroom setting can vary (Friel-Patti, 1999; Heine & Slone, 2008; Katz & Wilde, 1994; Lasky, 1983; Medwetsky, 1994; Schwartz & Gurian, 2003; Smoski, Brunt, & Tammahill, 1992). Children can present with either a few or many listening problems and behaviours. The challenges experienced may vary between children, or within a child across situations. When a child arrives at the audiology clinic the expectation is that an assessment of auditory processing and perception abilities will be conducted that is tailored to their needs, has sufficient scope to result in an accurate description of strengths and deficits, and ultimately provides the child, parents and educators with an understanding of the disorder as well as effective intervention strategies. The challenge for the audiologist is that there is no clear link between behavioural descriptions and a specific auditory ability or profile. This has led to the development and use of a test battery approach to the clinical assessment of auditory processing abilities.

1.2 Clinical Assessment of Auditory Processing Abilities

Clinical audiologists were assessing the auditory processing abilities of children for more than 20 years before the American Speech and Hearing Association (ASHA, 1996) published the first consensus statement on the topic. The 1996 report from the ASHA Task Force on Central Auditory Processing Consensus Development offered both a definition for central auditory processing and central auditory processing disorders. It also offered guidance for best practice in diagnosis and management. The ASHA Task Force agreed on the following definition:

> Central auditory processes are the auditory system mechanisms and processes responsible for the following behavioural phenomena:
>
> - Sound localization and lateralization
> - Auditory discrimination
> - Auditory pattern recognition
> - Temporal aspects of audition, including
>   - Temporal resolution
>   - Temporal masking
>   - Temporal integration
>   - Temporal ordering
> - Auditory performance decrements with competing acoustic signals

- Auditory performance decrements with degraded acoustic signals.

> These mechanisms and processes are presumed to apply to nonverbal as well as verbal signals and to affect many areas of function, including speech and language. They have neurophysiological as well as behavioural correlates. (ASHA, 1996, p. 43)

With this definition in place it followed that "A central auditory processing disorder (CAPD) is an observed deficiency in one or more of the above-listed behaviours" (ASHA, 1996, p. 43).

The first ASHA report (ASHA, 1996) and one that followed 10 years later (ASHA, 2005a) included recommendations for best practice for the assessment of auditory processing skills. The assessment recommendations advocated for a test battery approach. The battery should include an exhaustive case history, observation of the behaviours in question (conducted in person by the audiologist or through the administration of surveys and questionnaires), the behavioural evaluation of auditory abilities, the objective evaluation of the integrity of the auditory nervous system through electrophysiologic measures, and a speech-language assessment. The speech-language assessment should be completed by a speech-language pathologist as part of an interdisciplinary team approach. The case history and behavioural observation provide the audiologist with a context for parental or teacher concerns. This information can be used for the individualization of the assessment battery. The auditory processing assessment itself is recommended to include a standard assessment of hearing sensitivity that includes pure tone thresholds, speech audiometry, acoustic immittance and otoacoustic emission testing, and the assessment of auditory processing abilities. Each portion of the evaluation is expected to meet the recommended standards for hearing (ASHA, 1988, 1997, 2005b, 2006) and auditory processing (ASHA, 1996, 2005a) assessment.

Offering autonomy to the audiologist in the selection of specific test measures for the auditory processing assessment, the guidelines only dictate the framework and general content of this portion of the assessment battery. Specific tests are not recommended.

ASHA recommends inclusion of tasks that assess performance with competing acoustic signals, pattern recognition, and auditory discrimination. The details of how these are to be assessed are not well defined. Several tests measuring performance with a competing signal are available; for example, the SCAN-C (Keith, 2000a), the Staggered Spondaic Word test (Katz, 1998), or the Auditory Figure Ground (Ivey, 1969, 1987) and Competing Sentences tests (Ivey & Willeford, 1988). Tests of pattern recognition such as the Pitch Pattern Sequence test (Pinheiro, 1977), and the Duration Pattern Sequence test (Musiek, Baran, & Pinheiro, 1990) are also available. Tests of general auditory discrimination ability are less readily available to the audiologist.

Many clinicians, when asked about auditory discrimination testing would only include the repetition of single words in ideal quiet conditions (Emanuel, Ficca, Korczak, 2011). Tests incorporating minimally contrast pairs of words such as Wepman's Auditory Discrimination Test, Second Edition (Wepman & Reynolds, 1987), Goldman-Fristoe-Woodcock Test of Auditory Discrimination (Goldman, Fristoe, & Woodcock, 1970), Developmental Test of Auditory Perception (Reynolds, Voress, & Pearson, 2008), and Test of Auditory Processing Skills, Third Edition, (Martin & Brownell, 2005) are in use by speech-language pathologists. They are also confounded by top-down processing and are language specific. These speech tasks provide only a gross estimate of the discrimination and encoding abilities of the auditory system, given the extent to which word recognition relies on top down processing. For more detailed feature level discrimination to be assessed, different types of tests are required. As recent ASHA reports imply (ASHA, 1996; 2005a), there is increasing awareness of the importance of auditory discrimination assessment to estimate the processing of basic acoustic features in the time, frequency and level domains, without being subject to language factors:

> With the exception of speech and language tests that assess speech sound discrimination, there are few commercially available tests of auditory discrimination developed expressly for use in APD assessment and diagnosis. Yet the ability to discriminate among similar-sounding auditory stimuli is arguably one of the most important determinants of auditory processing ability. (Bellis, 2006, p. 72)

1.3 Acoustic Signal Encoding

All sound is comprised of basic physical elements that can be described by their spectral, level and temporal properties. To understand signals the ear must accurately detect, discriminate, and encode these physical properties for further analysis, comparison, and synthesis in the auditory nervous system. It is important that the encoding and transmission of features be accurate if signal clarity is to be preserved at all levels of the auditory system. Although some error in the encoding of signal features may be tolerated, especially with very familiar signals, poor encoding can lead to difficulty perceiving auditory signals. Determining an individual's ability to detect, or recognize small differences or changes in signals may provide some insight into the accuracy with which acoustic signals are represented in the auditory system. Ability to recognize small differences in a signal may suggest good signal encoding, while ability to recognize only large differences in features may suggest an impaired auditory system (Kidd, 2002).

A problem detecting and discriminating the acoustic features of a signal is likely to impact higher levels of processing in a negative way. For this reason, assessment of basic signal feature encoding should be an important component of a comprehensive assessment of auditory processing in children. Tests of auditory discrimination, employing rigorous psychophysical methods, have been conducted for many years in the laboratory setting. To this date, however there has not been a substantial transfer of these laboratory tests and methods to the clinical setting. Lack of suitable technology and the large number of trials typical of laboratory research have been limiting factors in the clinical implementation of signal feature encoding assessment. Advances in technology and digital signal processing that allow for the rigorous control of signals and test protocols now make it possible to transfer laboratory tests to the clinical setting. The adaptation of procedures to the testing of children inclines their use in clinical assessment. For example, Allen and colleagues (Allen & Wightman, 1992; Allen, Wightman, Kistler, & Dolan, 1989; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989) adapted test procedures used with adults to make them suitable for working with children. Modifications included the use of colourful graphics to guide children through a block of trials and to provide listening cues and feedback. They presented shorter trial blocks with more breaks to keep the test within the attention span of a young child. When using an adaptive test method these researchers showed that a sufficient number of reversal points could be obtained in a relatively short trial block to reliably estimate a threshold level. The use of feedback for each response promoted an impression of success and encouraged the children to complete the block of trials. Shorter, more numerous trial blocks allowed for both the natural and necessary breaks in testing a young child required while still allowing for good estimates of performance. Graphics to visually support the presentation of signals in a game-like format kept the children interested in completing the tests. The combination of these test procedures and advanced signal generation technology is the means through which these laboratory signal encoding tests can be transferred successfully into the clinical setting.

1.4 Auditory abilities in special populations

Laboratory results have provided a significant amount of information about the feature encoding ability of adults and typically developing children. Auditory processing and signal feature encoding has been investigated in a number of special populations including learning disabled, dyslexic, language impaired, and attention deficit disorders. The purpose for these investigations has been to better characterize the disorder and/or to determine their possible linkage with auditory impairment (Hickson & Newton, 2000; Katz & Wilde, 1994).

1.4.1 Learning disability

Assessment of auditory abilities in children with general learning disabilities has demonstrated performance ranging from the apparent absence of auditory deficits to the presence of severe auditory problems (Welsh, Welsh, & Healy, 1996). In a study of temporal resolution, as measured by the Auditory Fusion Test, McCroskey and Kidder (1980) found that learning disabled children demonstrated the largest fusion thresholds (poor temporal resolution) when compared to normal and reading disordered groups that were matched for IQ and age. Other investigations of temporal processing abilities in learning disabled groups resulted in less clear findings. For example, rapid auditory processing, as measured by a same-different discrimination of complex tone pairs presented in rapid succession, showed a correlation with academics but performance between the normal and impaired learners was similar for a number of conditions and only marginal differences were observed on others (Waber, Weiler, Wolff, Bellinger, Marcus, Ariel, Forbes, & Wypij, 2001). In studies where numerous auditory tasks have been included in an assessment of auditory skills in learning disabled groups, the reported co-occurrence of auditory deficits (temporal encoding) with learning impairment was 43% (Iliadou, Bamiou, Kaprinis, Kandylis & Kaprinis, 2009) and differences in performance were found on only some, not all, of the measures administered to the groups (Moav, Nevo, & Banai, 2009; Wright, Zecker, & McClelland, 2004). As a result of the age range included in the assessment of auditory skills in their study, Wright, Zecker, and McClelland (2004) postulated that not only do learning impaired individuals have co-occurring auditory perceptual deficits but that the deficits may be the result of delayed development. They suggested that the delayed development hypothesis is supported by the observation that older children demonstrating impaired auditory perception often achieve performance levels that are similar to younger, normal children. Wright et al. (2004) theorized that these developmental delays contribute to the auditory clinical presentation and learning problems of this population and that even if some auditory skills reach normal adult levels, the developmental delay may have interfered with the learning process to the point where residual disordered function persists.

The evidence indicates that children diagnosed with learning disability may have a concurrent diagnosis of auditory processing disorder. The rate of co-occurrence of these disorders in any study will depend on the age-range of the sample and the characteristics of the learning disability studied. Although not a wide range of signal encoding abilities have been investigated with learning disabled children there is evidence to suggest that temporal processing abilities in this group, as measured by gap detection and various masking paradigms, are poor in comparison to age-matched typically developing peers.

1.4.2 Attention Deficit Hyperactivity Disorders (ADHD)

Auditory and attention disorders share a similar clinical presentation and have a reported co-morbidity in children that ranges between 29 to 80% (Keller & Tillery, 2002). The somewhat frequent report of a concurrent diagnosis led to the question of whether ADHD and auditory processing disorders were the same entity, or if they had overlapping characteristics that may have a common underlying deficit (Chermak, Hall,& Musiek, 1999). Chermak and her colleagues (Chermak, Somers, & Seikel, 1998; Chermak, Tucker & Seikel, 2002) challenged the perception of overlapping characteristics when they found that groups of professionals, surveyed audiologists and psychologists, involved in the diagnosis of auditory and attention disorders demonstrated a clear differentiation of the clinical presentation and behaviours in these two groups. Using a combination of clinical auditory test measures and attention surveys, Riccio, Hynd, Cohen, and Molt (1996) found a co-occurrence of auditory and attention disorders of 55% in the group of children referred for testing in their study. Although the co-occurrence of these disorders was high, the correlation between the test scores was low suggesting that ADHD and auditory processing disorders may co-occur in children but are not the same entity. Auditory processing was investigated using the SCAN and Lindamood test batteries in a group of normal performing children and two clinical groups of children including one diagnosed as having ADHD and one with ADHD in combination with general learning disability (Gomez & Condon, 1999). The SCAN was considered by the authors to assess auditory perception and the Lindamood battery tapped concept comprehension. The three groups did not differ in age or IQ. Gomez and Condon (1999) found that the groups did not differ on the Lindamood subtest performance. The AHDH and normal groups did not differ in their performance on the SCAN subtests but the learning disabled with ADHD group demonstrated scores that were significantly poorer on the competing words subtest of the SCAN in comparison to the other two groups. The authors interpreted this finding as meaning that auditory processing disorders and attention disorders are separate entities and that they can co-occur in children experiencing learning problems. The conclusion that auditory perception and attention disorders are different entities but frequently co-occur in children has been supported by several studies that employed extensive test batteries using a variety of clinical test and auditory perception tasks (Cook, Mausbach, Burd, Gascon, Slotnick, Patterson, Johnson, Hankey, & Reynolds, 1993; Riccio, Cohen, Garrison & Smith, 2005).

1.4.3 Reading Impairment

Auditory perception has been investigated in children who demonstrate a range of impaired reading abilities. Using a battery of clinically available auditory processing tests, Dawes and Bishop (2010) found that approximately half of dyslexic children tested demonstrated an auditory processing deficit. Since the early studies by Tallal (1976) and colleagues (Tallal & Newcombe, 1978; Tallal & Piercy, 1973) into the ability to detect auditory signals separated by various inter-stimulus interval durations, the question frequently posed by studies investigating auditory perception in the reading impaired population involves temporal signal encoding abilities. Typically, these studies investigate the theory that children with language and/or reading impairment have difficulty processing short duration signals or signals that occur in rapid succession. Temporal processing deficits were confirmed by rapid auditory perception and temporal order judgment tasks by Heiervang, Stevenson and Hugdahl (2002) in a study with reading impaired individuals. They found that signal duration and rate of presentation were significant variables but proposed that memory may actually be the most relevant factor affecting the ability to process, accurately perceive, and respond to the acoustic signals. Cestnick and Jerger (2000) also reported poor rapid auditory perception in reading impaired groups of children. They suggested that variation in auditory performance may be related to the type of reading impairment (lexical or non-lexical) but did not report the same kind of memory influence observed by Heiervang et al. (2002). Measures investigating temporal signal encoding, other than rapid processing tests, have been used in studies with reading impaired children. In an investigation of age related changes on a gap detection task, Hautus, Setchell, Waldie and Kirk (2003) discovered very poor temporal resolution in the youngest age groups tested (6 – 9 years) but that by 10 years of age impaired readers were demonstrating similar performance to typically developing children and adults. This led to the same conclusion made by

Wright et al. (2004) that a delay in development of auditory perception results in lingering impaired function.

In a study with a large group of reading impaired individuals, aged 7 to 22 years, Fischer and Hartnegg (2004) administered a number of signal encoding tasks including gap detection, intensity and frequency discrimination, and signal order judgments. They reported poor signal encoding ability for all tasks at younger ages and normal adult-like performance for some but not all tasks with increasing age. When performance was considered as the number of tasks completed at levels above chance, a clear separation was observed between dyslexic and control groups across age. Boets, Wouters, van Wieringen, and Ghesquiere, (2007) conducted a longitudinal study with children considered at risk for reading impairment. Signal encoding was assessed through gap, frequency modulation, and tone-in-noise detection tasks. They found an overrepresentation of signal encoding problems in children with impaired reading abilities. In the dyslexic group investigated by Rosen and Manganari (2001) temporal processing deficits were identified through a backward masking task. Auditory perception problems in dyslexic children are not limited to temporal feature encoding. Elevated frequency discrimination thresholds have been observed in several studies involving dyslexic children (France, Rosner, Hansen, Calvin, Talcott, Richardson & Stein, 2002; Halliday & Bishop, 2006). Amitay, Ahissar, and Nelken (2002) investigated frequency discrimination ability as well as temporal processing ability as tested through tasks such as lateralization and amplitude modulation detection. They found that half of the reading impaired group demonstrated elevated (poor) frequency discrimination abilities and one third had overall poor auditory perception, showing that reading impaired children experience varying degrees of competence in spectral and temporal signal feature encoding.

The review of studies that assessed signal encoding abilities in reading impaired individuals revealed a frequent concurrent diagnosis of auditory processing disorder. The rate of co-occurrence of these disorders depended on the age-range of the sample group and the characteristics of the reading disability studied. Signal encoding abilities that have been investigated with reading disabled children include temporal and spectral features through a variety of tasks (gap detection, temporal order judgment, signal discrimination, etc.). Evidence from these studies suggested that temporal and spectral signal encoding abilities in one third to one half of the reading impaired population are poor in comparison to age-matched typically developing peers.

1.4.4 Specific Language Impairment

The link between hearing abilities and speech language development is well known but there are children that have normal hearing sensitivity and fail to acquire normal speech-language skills. Tallal and Piercy (1973) investigated auditory temporal processing in children who had normal hearing and impaired language development. Their hypothesis was that this group of children had failed to develop normal speech and language skills because the rate at which speech occurs was too fast for them to process. In experiments that manipulated presentation rate, Tallal and Piercy (1973) found many language-impaired children had difficulty with temporal feature encoding. Since publication of this study, the ability of language-impaired children to encode signal features has been investigated (Rosen, 2003). Some of the signal encoding abilities identified as disordered in children with diagnosed specific language impairment include amplitude envelope and duration cues (Corriveau, Pasquini, & Goswami, 2007), signal parametric comparisons such as temporal order judgment (Banai & Ahissar, 2006), rapid auditory processing as measured with brief inter-stimulus-intervals (Tallal, Merzenich, Miller, & Jenkins, 1998), frequency discrimination (Hill, Hogben, & Bishop, 2005; McArthur & Bishop, 2004a, 2004b; Nickisch & Massinger, 2009), and masked signal thresholds (Hartley & Moore, 2002). Although children with language and/or reading delays may demonstrate poor performance on auditory perception tasks such as temporal order judgment, frequency discrimination, binaural processing or backward masking tests of signal encoding, it is evident that this is not the case for all children (Bailey & Snowling, 2002). Co-occurrence of auditory deficits in children with language impairment has been reported to exist in 40 – 50% of cases (Boets, Wouters, van Wieringen, & Ghesquiere, 2007; McArthur, Ellis, Atkinson, & Coltheart, 2008; Rosen, 2003; Sharma, Prudy, & Kelly, 2009) but there have been studies where more or less than 50% of children in a study group demonstrate a co-morbidity (Bishop & McArthur, 2005;

Wright, Lombardino, King, Puranik, Leonard, & Merzenich, 1997). It is likely that this range of concurrent presentation is a result of the characteristics of the study sample. As an example, studies report that memory has also been identified as an area of weakness in children with language and discrimination deficits (Fernell, Norrelgen, Bozkurt, Hellberg, & Lowing, 2002; Norrelgen, Lacerda, & Forssberg, 2002) so if a sample group did have a higher incidence of memory deficits this may impact the overall study outcome.

A high prevalence of auditory processing disorders has been identified in children diagnosed with specific language impairment (Dawes & Bishop, 2009). In the review of studies that assessed signal encoding abilities in children with language disorders, poor performance was identified in temporal and spectral features as measured through a variety of tasks (e.g. gap detection, temporal order judgment, signal discrimination). Evidence suggested that difficulty encoding temporal and spectral signal features is commonly observed in children with language impairment.

1.4.5 Auditory Processing Disorder

The presence of auditory processing deficits and reduced signal feature encoding abilities has received attention in a variety of special populations. However, signal feature encoding abilities in children suspected of having an auditory processing disorder have not been well studied even though it has been hypothesized that poor signal encoding may be a contributing factor to listening skill deficits in some of them (Moore, 2006; Vanniasegaram, Cohen, & Rosen, 2004). The number of investigations into signal encoding abilities in a confirmed or suspected APD population has been very limited (Hurley & Fulton, 2007). McFadden (2006) investigated prosodic understanding in a group of normal children and a group of children identified with auditory processing disorder. Included in the study were tests of spectral, level and temporal encoding. Findings indicated that signal encoding abilities, including discrimination of frequency and intensity differences, gap detection, and temporal integration of some children with APD were poor in comparison to a group of normal developing children. The poor signal encoding abilities observed in the study clinical population appeared to have a negative impact on the ability to detect and identify prosodic cues. Dawes, Bishop, Sirimanna and Bamiou (2008) conducted a retrospective study of a research database that included children assessed for auditory processing disorder. The retrospective review included questionnaires about auditory behaviour, medical histories and auditory processing measures. Some children diagnosed with auditory processing disorder demonstrated poor temporal encoding abilities as measured by the Random Gap Detection Test (Keith, 2000b) and the Gaps in Noise Test (Musiek, Shinn, Jirsa, Bamiou, Baran, & Zaidan, 2005). Auditory processing in children attending a UK school system was investigated by Moore, Ferguson, Edmondson-Jones, Ratib, and Riley (2010). Test measures employed in this study included acoustic signal encoding, communication and hearing checklists, as well as the evaluation of attention, cognition, memory, phonology, and reading. Signal feature encoding tests included frequency discrimination, frequency resolution, temporal resolution, and masked signal detection. Considerable variability in performance was reported both within and between listeners on tests of signal encoding. Investigators reported that performance improved with increasing age and adult performance was achieved for all tests between 7 and 9 years of age. The analysis of individual performance revealed that children with poorest signal encoding abilities, across test measures, also demonstrated poorest performance on listening, communication, language, and literacy tests. The researchers concluded that signal encoding may be a problem for children suspected of having auditory processing problems. Based on this small number of studies, there is an indication that some children with auditory processing deficits may have difficulty encoding acoustic signals.

Unfortunately the scope and extent of signal feature encoding deficits in children suspected or identified with auditory processing disorder remains unknown. Further investigation into the prevalence and nature of signal feature encoding problems in children referred for auditory processing assessment is important for improving the understanding of this disorder (Rosen, 1999) for at least three reasons. First, if only some children in the clinical population suspected of having an auditory processing disorder have poor signal feature encoding abilities, this may be an important differential diagnostic tool to direct children into appropriate treatment programs based on the nature of the auditory disorder. The second reason to achieve a better understanding of signal feature encoding in children relates to the development of treatment programs. A clear indication of whether auditory deficits include signal encoding problems and specification of the type of encoding difficulty can lead to more effective intervention programs that efficiently target areas of weakness. Finally, if inefficient and inaccurate encoding of signal features is a known contributing factor to the lack of normal language and reading ability development in some children, then early identification of signal encoding problems can become instrumental in development of early intervention programs to reduce the negative impact of these disorders in at-risk children. At present, very little is known about the extent to which acoustic signal encoding is disordered in children suspected of having auditory processing disorder and the degree to which presently available clinical tests of auditory processing abilities reflect signal encoding abilities. Although many recent studies, as described earlier, evaluate the contribution of signal feature encoding to other disorders, or describe signal encoding in groups of children attending regular or learning disabled classrooms, there have been few studies attempting to evaluate signal feature encoding in a systematic way in a group of children suspected of auditory processing disorder. This project was a group of studies designed to address the gap in understanding of acoustic signal feature encoding in children referred for auditory processing disorders.

1.5 Statement of Purpose

This project investigated basic signal encoding abilities of children suspected of having an auditory processing disorder. The signal features selected for investigation were chosen to address the three properties of acoustic signals including spectral, level and temporal aspects of sound, and identify those areas that might be most problematic in this clinical population of children. With potentially several areas of signal feature encoding difficulties in children suspected with auditory processing disorder (McFadden, 2006), the study was designed to have sufficient scope to direct future research to features that would result in the most sensitive diagnostic tools, and to develop the most necessary treatment programs. Spectral encoding ability was assessed through measurement of both frequency resolution, via the notched noise masking masker procedure, and frequency discrimination, via the evaluation of a just noticeable difference for frequency. Intensity discrimination ability was assessed via evaluation of a just noticeable difference for level. Temporal processing was assessed through a measure of temporal resolution (gap detection) and a measure of temporal integration at threshold.

There were two key questions posed for this study:

- Do children with auditory processing disorder experience poorer signal encoding than normally developing children?
- Do children who demonstrate learning and behavioural problems without meeting the criterion for auditory processing disorder have reduced encoding abilities?

Also of interest was whether there was consistency in performance across tasks.

Chapter 2

2 General Method

The method described in this chapter applies to all studies included in this project unless otherwise stated.

2.1 Ethics Approval

Approval of this project was secured from the University of Western Ontario, Office of Research Ethics (Appendix A). Parents were required to read the study Letter of Information and sign a consent form for study participation prior to the child's enrollment in the study (Appendix B). Verbal assent was obtained from each child at the beginning of the study and continued to be obtained from the participant on an ongoing basis in advance of each measure or activity during the test sessions. There was no penalty for withdrawal from the study.

2.2 Participants

The participants in this study were part of a larger group of children participating in a comprehensive study investigating auditory processing disorders. School-aged children were recruited from the London, Ontario and surrounding area by way of the letter of information that invited typically developing children and children with, or suspected as having, an auditory processing deficit to participate in a study of hearing and auditory processing (listening). The letter was provided to local schools and audiology clinics for distribution to families. Individuals who contacted the researchers after hearing about the study through other sources were provided with the letter of information and, if interested, also participated in the study. All participants were native English speakers. Because the participants were involved in a larger project the number, age range and gender of children varied across signal feature encoding study. A total of 59 children, 21 female and 38 male, ages 7.2 to 16.6 and 7.2 to 17.6 years respectively, participated in the studies. Some children may have completed more than one signal encoding study, depending on the date of entry and continuing participation in the project. Of the 59 children enrolled, 12 completed all 5 of the signal feature encoding studies. Figure 1 displays the age and gender distribution for overall study participation. It shows that the male participants outnumber the females by a factor of two, reflecting the general reports of referral demographics for auditory processing assessment in clinical settings (Keith, 2004). Anecdotal reports from typical audiology clinics and some prevalence reports (Chermak, 2002; Keith, 2004) suggest that a higher number of boys than girls are referred for auditory processing assessment and that children are referred at younger rather than older ages.

To be enrolled in the study the participants were required to demonstrate normal pure tone thresholds and middle ear function (ASHA 1988, 1997). During the hearing test, participants sat comfortably in an IAC double-walled sound isolation room (controlled acoustical environment) where pure tone thresholds for 250, 500, 1000, 2000, 4000 and 8000 Hz were obtained bilaterally, employing conventional test methods. The Interacoustics AC40 Clinical Audiometer was used to obtain the hearing thresholds. Signals from the AC40 were routed through Etymotic Research EAR 5A insert earphones coupled to the ear with sponge insert eartips. Participants sat comfortably in a quiet room adjacent to the sound isolation rooms for the assessment of middle ear function. The Grason Stadler Tympstar diagnostic middle ear analyzer assessed middle ear function for both ears by obtaining tympanograms as well as ipsilateral and contralateral acoustic reflexes at 500, 1000, and 2000 Hz. Following the hearing assessment children with normal hearing sensitivity were entered into the study. If a child was excluded from the study due to hearing loss and/or middle ear dysfunction, their parents were informed of their child's hearing assessment results and they were referred to the appropriate community professionals for follow-up. Thresholds for individual listeners fell within the normal range. Hearing thresholds, averaged across the frequency range, for the group of 59 children were 2.89 dB HL with a standard deviation of 4.61 dB in the right ear and 4.24 dB HL with a standard deviation of 4.39 dB in the left ear.

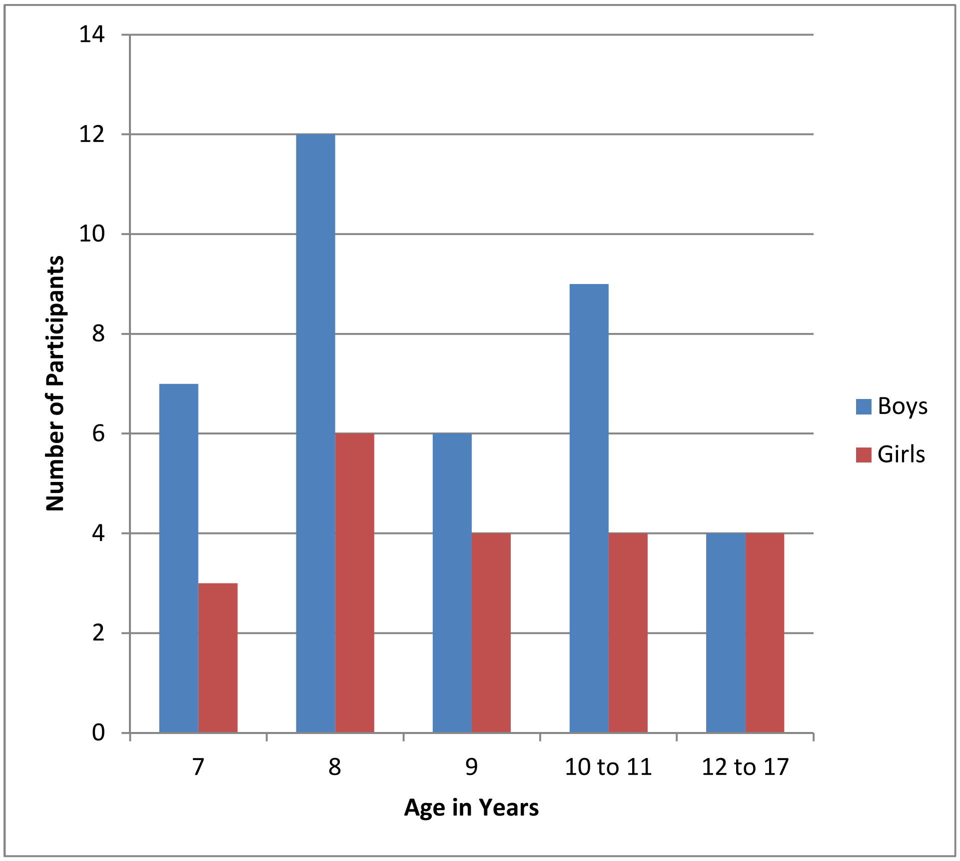


Figure 1 Age and gender distribution for all project participants.

The cognitive, academic and language abilities of the participants were assessed as part of the larger project. One participant did not undergo assessment in these areas. Standard scores were obtained for 58 participants on the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997) (PPVT), the Oral and Written Language Scales (Carrow-Woolfolk, 1996) (OWLS), the Wide Range Achievement Test (Wilkinson, 1993) (WRAT), and the Wechsler Abbreviated Scales of Intelligence (Wechsler, 1999) (WASI). The average standard score (standard deviation) on the PPVT, a test of receptive vocabulary, was 101.66 (14.52), revealing that the group had age appropriate receptive vocabulary abilities. The WRAT Reading and Arithmetic average standard test scores (standard deviation) were 87.91 (16.33) and 87.90 (15.06) respectively. The scores reflect the lower than average academic performance of this group of children. The average WASI Full Scale IQ standard score (standard deviation) for the group of children was 99.62 (15.81) showing that the children participating in this study have intelligence scores within the normal range. The mean standard scores (standard deviation) for the OWLS Comprehension and Oral Expression tests were 90.74 (13.53) and 91.03 (13.29) respectively for the group of participants. These results show that the receptive and expressive language abilities for this sample of children fall within the normal range.

As would be expected in a clinical population of children referred for auditory processing assessment, the children participating in this study were experiencing some level of academic failure. The children had either been identified as having an auditory processing deficit (determined by a community audiologist using a typical clinical test battery) or, as in most cases, concern was being expressed by teachers and/or parents about the participant's auditory skills and their ability to listen in a classroom setting. The reported auditory difficulties experienced by the participants were representative of referrals to community clinics for assessment of auditory processing abilities and for this reason qualified the group as a typical clinical population.

2.3 Clinical Auditory Processing Assessment

All children completed five commercially available auditory processing tests to confirm a diagnosis of auditory processing disorder, in keeping with the ASHA 2005a and American Academy of Audiology (AAA) 2010 recommendations for a test battery approach. The auditory processing test battery included the Filtered Speech test (Ivey & Willeford, 1988), the Auditory Fusion Test – Revised (McCroskey & Keith, 1996), the Pitch Pattern Sequence test (Pinheiro, 1977), the Staggered Spondaic Word test (Katz, 1998), and the Words in Ipsilateral Competition (Ivey, 1987) test. The Filtered Speech test is a monaural low redundancy test and was selected to assess auditory closure abilities and address performance with degraded acoustic signals. The Auditory Fusion Test – Revised was selected because it was one of the few commercially available tests of auditory fusion or gap detection able to evaluate temporal resolution abilities. Pitch Pattern Sequence is a test able to evaluate auditory sequencing, temporal ordering, and pattern recognition abilities. The Staggered Spondaic Word and Words in Ipsilateral Competition tests evaluate performance decrements in competing signals through the assessment of dichotic listening and auditory figure-ground discrimination abilities. In combination these five tests evaluate four of the six major classes, of behavioural phenomena ASHA (2005a) describes as reflecting the underlying mechanisms of auditory processing that include sound localization, auditory discrimination, auditory pattern recognition, temporal processing, auditory performance with competing acoustic signals and auditory performance with degraded acoustic signals. Test order administration was randomized. All tests were available as compact disc recordings and were played in a JVC XL-Z232 Compact Disc Player. Children were comfortably seated in an IAC double walled sound isolation room across from the examiner who could be viewed through the isolation room window. Auditory signals from the CD player were presented at the recommended levels by way of the Interacoustics AC40 Clinical Audiometer. The signals leaving the audiometer were heard by the participants through Etymotic Research EAR 5A Insert Earphones coupled to the ear with sponge insert eartips. Test instructions were provided as dictated by the instruction manual through the earphones by way of the AC40 talk forward capabilities. Further explanations of the test and response requirements were provided if requested or required by the participant. Tests were administered in sequence which provided a short break between tests as the CDs were changed and the audiometer adjusted as required for accurate test presentation. During this break children were reassured and encouraged to continue their good work.

Upon completion each test was scored according to its standard directions and compared to the normative data provided in the test manual. Chermak and Musiek (1997, Chapter 4) recommended that a diagnosis of APD be made if a single test result fell at greater than 3 standard deviations below the age mean or if 2 or more test scores fell at greater than 2 standard deviations below the age mean. These criteria for APD diagnosis have been generally accepted as a guide for clinical practice. Designation of an auditory processing disorder (APD) was made if 2 or more tests fell at greater than two standard deviations below the age mean. The results obtained from the auditory processing assessment battery are displayed in Figure 2 as a bar graph representing the total number of children that failed each test. There was a higher failure rate for some tests than for others. Highest failure rates were observed for the Auditory Fusion Test – Revised, the Staggered Spondaic Word test, and the Pitch Pattern Sequence test. These tests represent the assessment of temporal processing, auditory pattern recognition and performance with competing acoustic signals. The lowest failure rates were seen for the Filtered Speech and Words in Ipsilateral Competition tests that represent the assessment of performance with degraded and competing acoustic signals.

The children who participated in this study were part of a clinical population. All were experiencing some level of academic failure and displaying behaviour that suggested the possible presence of an auditory processing disorder. Figure 3 shows the proportion of children that met the recommended criteria for diagnosis with an Auditory Processing Disorder (APD), according to age. As can be seen in Figure 3, more than half of the children in all but the oldest age group met the criteria for auditory processing disorder diagnosis. The oldest age group had only 3 participants and only 1 of 3 children received the diagnosis. In total, 35 children of the total 59 participants met the criteria for a clinical diagnosis of auditory processing disorder. The remaining 24 children did not receive a clinical diagnosis but were included as part of a clinical non-APD group.

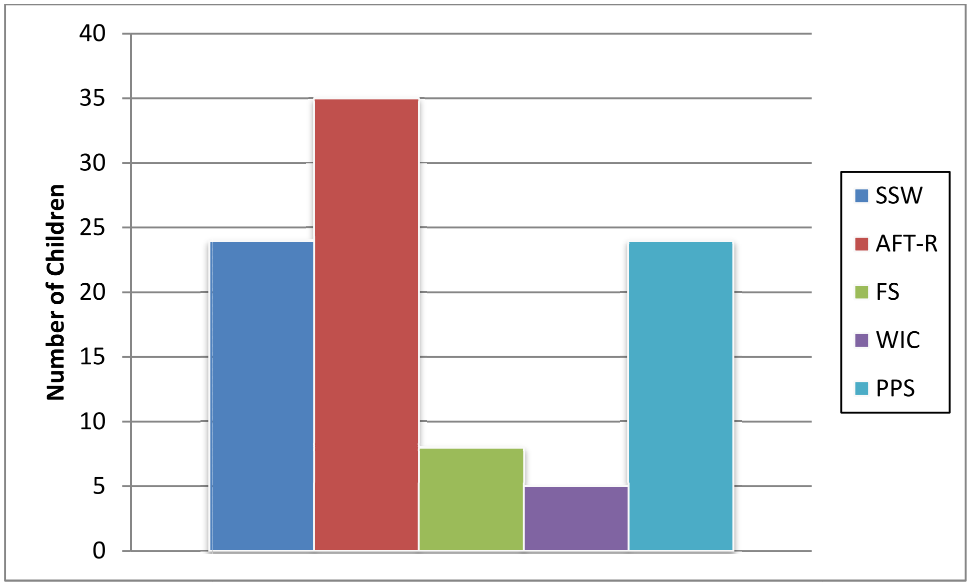


Figure 2 Number of children who failed (performance at or greater than 2 standard deviations below age mean) each test included in the auditory processing test battery (SSW=Staggered Spondaic Word test; AFT-R=Auditory Fusion Test – Revised; FS=Filtered Speech Test; WIC=Words in Ipsilateral Competition test; PPS=Pitch Pattern Sequence test).

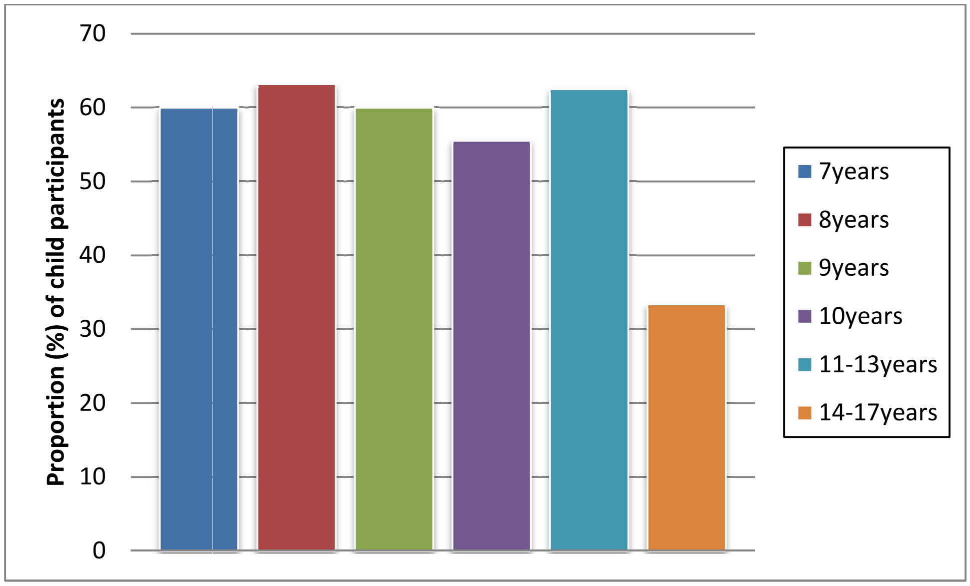


Figure 3: Proportion of child participants who met the clinical requirements for a diagnosis of auditory processing disorder diagnosis shown according to age group.

It should be kept in mind that all children included in this study presented with behaviour that suggested the presence of auditory skill and/or learning deficits. For the purpose of evaluating the data obtained from the clinical auditory processing assessment, the children were allocated into groups based on their test performance. The non-APD group included those children that did not meet the clinical test battery diagnostic criteria for auditory processing disorder. The APD group of children had two or more test scores that qualified them for a diagnosis of auditory processing disorder.

2.4 Procedure

All testing was completed at The University of Western Ontario Child Hearing Research Laboratory. Children attended at least one full day test session which allowed for sufficient time to complete the testing. Most children attended more than one day of testing to complete all the required measurements in the larger comprehensive auditory processing research project. Periodically, participants were offered rest breaks and refreshments. At the completion of testing each participant was given his/her choice of a small toy or school supply as thanks for their participation in the study.

2.5 Evaluation of acoustic signal feature encoding

Thresholds in all studies were estimated using an adaptive three Alternative Forced Choice (3AFC) task with feedback. The adaptive 3AFC method of obtaining psychometric thresholds, also referred to as the "oddball" or "odd-man-out" paradigm, has been used extensively with children and adults. Instructions for the task are simple and easily understood by children. The listener is presented with three signals in series. Two signals are identical (or standard signals) and a third is the target. The third is different from the standards. The target can occur in any of the three intervals with equal a priori probability. The target stimulus is varied on the feature of interest in such a way that the just noticeable difference threshold can be identified.

A two-down, one-up adaptive procedure as described by Levitt (1971), tracking the 70.7% correct response level, was employed. With this procedure the signal feature of interest in the target is reduced (the difference between the target and standard is decreased) after two consecutive correct responses or increased (the difference between the target and standard is made larger) following one incorrect response. For the signal feature being evaluated, the starting value for the target was very different from the value in the standard signal so that the target signal could be easily detected by all listeners. The target signal feature was varied adaptively with an initial large step size until the first reversal. A reversal is the trial response which meets the criteria for a change in the direction of the adaptive procedure that increases or decreases the distance of the target from the standard signals. Each subsequent reversal resulted in a change of the increase or decrease step size by the target toward or from the standard signal until an established minimum was achieved. The first reversal point was not included in the threshold calculation.

The forced choice paradigm employed in this study was presented in a video game format similar to the one developed by Wightman et al. (1989). A number of different animated and colourful graphics were available to assist in maintaining participant interest in the task. During each trial, the listener was presented with a 3 item visual graphic on the touchscreen monitor. Graphics included flowers, rain clouds, fish, clowns, or balloons in the foreground and the background was a scene appropriate to the item in the foreground or a solid colour with no graphics. Initiation of every trial was clearly indicated by the sequential appearance of the three identical foreground graphic items. In succession, each graphic changed colour or animation to indicate signal presentation (one target and two standard signals). The listener's task was to touch the graphic they believe corresponded with the target signal presentation. The target stimulus was presented in either the first, second, or third position and the computer employed an a priori probability of 0.33. Following the listener's selection, feedback was provided for that trial. The graphic items then exited the screen, clearly marking the end of the trial at which point the next trial would commence. For each block of trials a small indicator would track progress by moving from right to left horizontally or from bottom to top vertically, allowing the children to easily identify how far they had advanced in the task. Figure 4 shows an example of the series of computer graphics employed for the listening tasks.

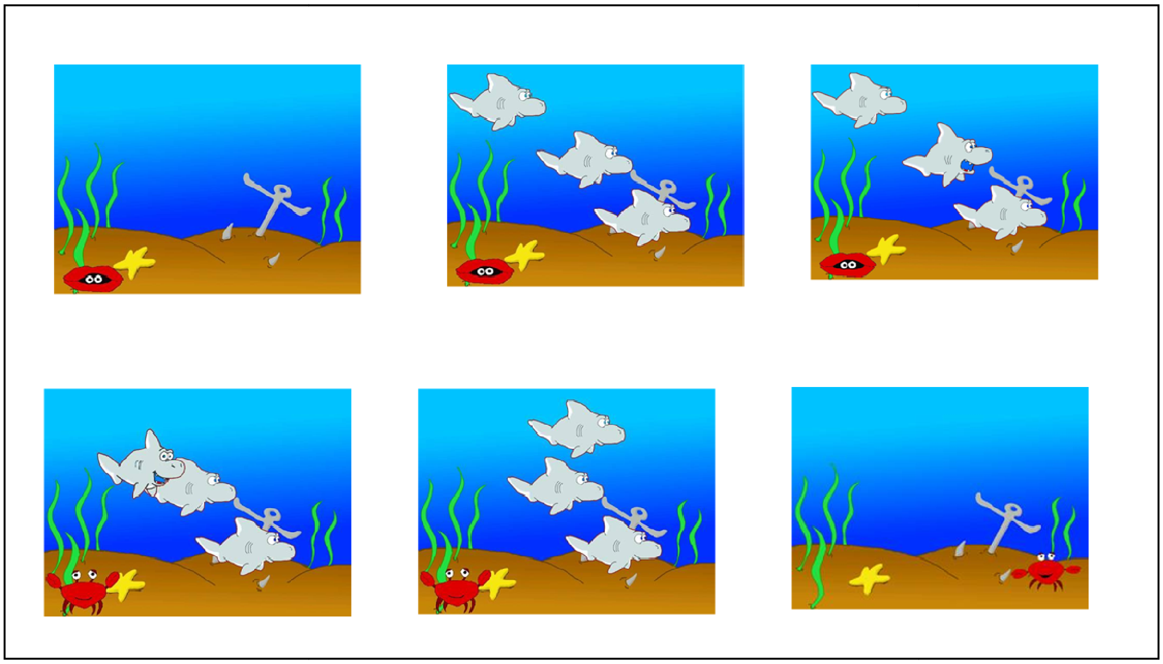


Figure 4 Sample screen-shots from one of the video game graphics show different elements of the signal encoding task. The upper three slides demonstrate the opening backdrop (left); three fish swimming into view indicating that a new trial is about to begin (middle); tone presentation associated with the fish opening mouth (right). The lower three slides demonstrate the bouncing, smiling fish that is offered as positive feedback for a correct response (left); fish swimming out of view indicating the end of the trial (middle); end of the block with the crab that travelled from left to right as an indication of the block progression.

During testing the listener and examiner were seated comfortably at a small table in the sound isolation room. The touchscreen monitor was located on the table facing the listener. The listener was instructed that their task was to watch the monitor, listen carefully and then touch the graphic on the monitor that "sounded different". An Etymotic Research ER-3 earphone with a foam-tip coupler was placed in the listener's right ear and an E.A.R. soft regular size earplug was placed in the left ear to reduce the interference of any possible extraneous HVAC noise during the test session. Listeners completed a minimum of three blocks for each different test condition. Listeners were administered additional blocks of trials if there was a technological malfunction or if the block was not completed. The researcher sat with the listeners and monitored the progress of trial blocks and performance. Trial blocks were discontinued if requested by the listener. Trial blocks were also discontinued if the listener and/or examiner reported a problem with the test signals. For example, the child or examiner may have reported that the signals could no longer be heard or that the signals didn't sound the way they had previously. By monitoring the number of correct or incorrect target identifications made by the listener, the examiner was able to discontinue and restart the block of trials if the listener was clearly being inattentive to the task or was not following task instructions. The ability to discontinue and restart trial blocks provided the opportunity to reduce the likelihood that inattention contributed to poor thresholds. Each block was composed of 30 trials and enabled an estimation of threshold. For each study the listener completed a minimum total of 90 trials organized into 3 blocks. Participants had a scheduled break during the session between measures and were allowed to take additional rest breaks upon request. Actual test time took approximately 20 minutes for each condition which included three blocks of thirty trials. Following each measure the participants were commended for the successful completion of the task and, in compliance with the approved protocol, they were given a small toy or school supply as thanks for their participation in the study upon completion of all measures.

Thresholds were calculated upon completion of trial blocks. The threshold for a block of trials was obtained from an average of the midpoints between the reversal points in the block of trials. Trial blocks were considered for threshold calculation if a minimum of 4 reversal points were achieved. In this project, all participants achieved a minimum of 4 reversals on all trial blocks. Thresholds for each block of trials were averaged to achieve a single threshold for each condition completed by the listener.

2.6 Signal Generation

The signals for the frequency resolution, intensity discrimination, temporal integration (brief tone) and gap detection studies were generated digitally with the Tucker-Davis Technologies (TDT) System 3 RP2 real-time signal processor and controlled by a Dell Dimension 8100 desktop computer. The Dell computer and TDT System were located outside the IAC sound isolation room to reduce the amount of listener exposure to equipment noise during the test session. The signals were digitally generated with a 50 kHz sampling rate and processed through a 24-bit Sigma Delta digital-to-analog converter. The signal output from the HB7 headphone driver was connected, through the patch panel, to an Etymotic Research ER-3A transducer earphone located in the sound isolation room where the listener received the test signals. Stimuli for the frequency discrimination task were controlled and generated digitally by a Dell Dimension 8100 desktop computer, with 16-bit resolution, and converted to analog form at a 44100 Hz output. The signal output was connected, through the patch panel, to an Etymotic Research ER-3A transducer earphone located in the sound isolation room where the listener received the test signals. An elo Touchsystems 15"CRT Touchmonitor Model 1525C was used to display the psychoacoustic task graphic images associated with the acoustic signals and to record the participants' responses to the stimuli when they touched the image they believed represented the target stimulus.

The timing for signal presentation, controlled by the Dell Dimension computer, was set so that the visual animation that indicated signal presentation was 600 ms in duration. Visual and auditory presentation was synchronized by signal presentation onset. The acoustic signal was presented during the animation and this animation timing remained constant regardless of the duration of the signal or the presence/absence of a signal.

Level calibration was conducted acoustically through the experimental set-up prior to the initiation of the study and then routinely throughout the duration of the study.

Calibration was completed with a Bruel and Kjaer measuring amplifier (Type 2610) and associated preamplifier (Type 2639 with Adaptor DB1021), microphone (Type 4144), and artificial ear (Type 4152). Noise floor measurements were conducted with a Bruel and Kjaer Hand Held Analyzer (Type 2250) and associated preamplifier (Type 2669) and coupler system (Bruel and Kjaer 4157 Ear Simulator with integrated Type 4131 microphone).

2.7 Signals

The selection of specific signal parameters for a given encoding task can be challenging. Although one feature of a signal may be under investigation, the other signal features and to some extent the demands of the listening task itself can influence thresholds achieved by the individual. For example, if frequency is the feature under investigation, the frequency, level and duration of the signal can influence threshold outcome. Each of the five studies that compose this project required signals that would be unique to the encoding ability being investigated and demanded feature selection specifically for that purpose. The added complication to signal selection for this project was the goal to examine the listener performance both within and across encoding studies. The desire to compare listener performance across studies increased the challenge in signal parameter selection because to make this kind of comparison there is a need to have common features in all signals used in the study. A common thread in signal composition across studies allows for comparisons in performance and provides the opportunity to glean some insight into the signal encoding abilities of the auditory processing disordered population. For the purpose of this project, 1000Hz was selected as the test frequency for signals used in these studies. In regards to spectral encoding, the ear is most sensitive at 1000Hz and has been shown to result in some of the lowest discrimination thresholds in comparison those obtained with higher frequencies (Jesteadt & Sims, 1975; Maxon & Hochberg, 1982; Moore, Ferguson, Halliday & Riley, 2008; Sek & Moore, 1995; Yost, 2007, Chapter 10) which is the reason for the selection of this frequency for the assessment of several signal encoding studies.

Chapter 3

3 Frequency Discrimination

Frequency discrimination or the just-noticeable-difference for frequency refers to the smallest change or difference in frequency that can be perceived by a listener. The just-noticeable-difference threshold is referred to as a difference limen, which reflects the sensitivity of the listener to changes or differences in the signal parameter being investigated. Difference limens for frequency have been extensively researched, particularly in adults.

3.1.1 Frequency discrimination in adults

Discrimination thresholds for pure tones in adult listeners are generally 1 – 2% of the frequency being tested but threshold increases as frequency increases beyond 1000 Hz. (Yost, 2007, Chapter 10). Best performance is expected in the mid-frequency range between 400-2000 Hz. An increase in frequency discrimination threshold estimates can be observed for the frequencies higher and lower than the midrange, but the magnitude of the change in threshold estimates is greater for the higher frequencies, for example between 2000 and 8000 Hz (Sek & Moore, 1995; Wier, Jesteadt, & Green, 1977). Discrimination of frequency difference varies with signal level such that performance across frequency is better at higher levels (40 – 80 dB SL). Frequency discrimination thresholds at low signal presentation levels (10 – 20 dB SL) will result in elevated (poorer) thresholds. The effect of signal level on frequency discrimination is greatest for low frequency stimuli and demonstrates less influence on discrimination thresholds in the mid (400 – 2000 Hz) and high (2000 – 8000 Hz) frequencies. (Freyman & Nelson, 1991; Wier, Jesteadt, & Green, 1977).

3.1.2 Frequency discrimination in typically developing children

Typically developing children generally show poorer frequency discrimination thresholds than do adults although the age at which children achieve adult-like performance varies across studies. Maxon and Hochberg (1982) conducted a series of studies with 4-12 year old children on a number of auditory discrimination tasks, one of which was frequency. Four frequencies were tested including 500, 1000, 2000, and 4000 Hz at a 30 SL presentation level. The task was a same-different paradigm. Frequency discrimination improved with increasing age and reached adult levels at 12 years. Children demonstrated the same effect of frequency on discrimination thresholds that was observed for adults. Thresholds were best (lowest) in the mid-frequency range. Frequency discrimination thresholds at 1000 Hz were 9.5 Hz for the 6 year old group of children but improved to 3.7 Hz for the 12 year olds. A similar developmental trend for children using a 3AFC task was demonstrated in a study of several auditory discrimination tasks with 4-6 year old children conducted by Jensen and Neff (1993). Frequency discrimination was assessed for a 400 Hz pure tone signal presented at 70 dB SPL. An improvement in threshold with age was observed. Only some of the children in the 6 year age group achieved adult-like thresholds. Average thresholds were estimated at 70 Hz for the 4 year olds, 6 Hz for the 6 year olds, and 2 Hz for adults. There was a significant amount of inter-subject variability observed in the data. Thompson, Cranford and Hoyer (1999) conducted a series of frequency discrimination tasks with children aged 5 – 11 years and adults. Thresholds were obtained for 1000 Hz signals presented at 75 dB SPL and three signal durations (20, 50, and 200 ms). The 5 and 7 year old children demonstrated the poorest thresholds for all signal durations. Adult discrimination thresholds were achieved by 9 years of age. Frequency discrimination thresholds at 1000 Hz were reported for children aged 6 – 11 years and young adults by Moore et al. (2008). In a 3 AFC procedure they found that younger children demonstrated more variability between and within blocks of trials and higher mean thresholds. Discrimination thresholds for a 200 ms 1000 Hz signal improved (decreased) with increasing age and although mean thresholds were significantly different between age groups, some of the children's thresholds fell within the adult range. Mean frequency discrimination threshold was approximately10% of the centre frequency for the youngest age group (6-7 year olds) and improved to approximately 3% of the centre frequency for adults. Thresholds in the Moore et al. (2008) study were higher than those reported by Jensen and Neff (1993) and Maxon and Hochberg (1982) but this may be due to the shorter signal duration. Another contributing factor to the higher thresholds was that the Moore et al. (2008) study was conducted in the school setting. Their sample may therefore have included children that were not typically developing but still attending the regular classroom. This sampling process may have resulted in elevated average discrimination thresholds in comparison to studies which only recruited typically developing children.

3.1.3 Frequency discrimination summary

In summary, typically developing children demonstrate a developmental trend in their ability to discriminate frequency differences. Large variability is observed in the performance of children, particularly younger ones, and adult-like threshold values are not achieved until 8 to 12 years of age. Best performance on frequency discrimination tasks has been observed with mid-frequency signals (400 – 2000 Hz) that are clearly audible (level greater than 30 dB SL) and have durations greater than 200 ms.

3.2 Method

The frequency discrimination study adheres to the General Method as described in Chapter 2. This study-specific method section describes the participants as well as the signal parameters and procedures that were unique to the frequency discrimination study.

3.2.1 Participants

There were forty-seven children, 17 girls (7 – 16 years) and 30 boys (7 – 17 years) who participated in this study. All the children participated in the larger study investigating auditory processing abilities in children. The clinical classification of children into APD and non-APD groups resulted in 23 children falling into the non-APD group and 24 children obtaining a diagnosis of APD (based upon 2 or more of the 5 behavioral tests of central auditory function falling more than 2 standard deviations below expectations).

3.2.2 Signals & Procedure

The signals were samples of pure-tones digitally generated by a Dell Dimension 8100 desktop computer, with 16-bit resolution, and converted to analog form at a 44100 Hz output. Stimuli were 500 ms in duration, separated by a 400 ms inter-stimulus interval. Stimuli were gated on and off by a 10 ms cosine squared ramp. All stimuli were presented at an intensity of 65 dB SPL. The standard signals were set at 1000 Hz. The initial target signal for each block was 1200 Hz. The upper limit of the target stimulus frequency was 3500 Hz and lower limit was 1000 Hz. The target stimulus changed in an adaptive manner in increments relative to the standard stimuli. Two consecutive correct responses resulted in a reduction of the target frequency by a factor of 0.7143. One incorrect response resulted in an increase of the target frequency by a factor of 1.4. Thresholds for the target, adapting signal, were obtained using the adaptive three alternative forced choice oddity paradigm as described in the general method.

3.3 Results

All forty-seven children completed three thirty-trial blocks of the frequency discrimination test. Thresholds were calculated for each block. Minimum requirements and threshold calculation was achieved as described in the general method. A one way within subjects repeated measures analysis of variance was conducted for the three blocks of trials. A statistically significant difference was not found between threshold estimates for the three blocks of trials, Pillai's Trace = 0.33, $F(2,45) = 0.775$, $p = 0.467$, $\eta^2 = 0.033$. Because there was no statistically significant difference between trial blocks, the three threshold estimates were averaged to produce a single discrimination threshold estimate.

Figure 5 shows individual listeners' thresholds plotted on a logarithmic scale as a function of child's age. Data from the children identified as APD and those not are shown by the open red square and open blue diamond symbols, respectively. The solid green triangles, solid violet diamonds, and the solid gold circle represent the average thresholds obtained from typically developing children and adults as reported in the Jensen and Neff (1993), Maxon and Hochberg (1982), and Freyman and Nelson (1991) studies respectively. It is evident from Figure 5 that many of the children participating in this study had discrimination thresholds that were elevated in comparison to those reported for typically developing children of the same age. The ranges for individual threshold scores were similar for the two diagnostic groups: non-APD thresholds ranged from 8.72 – 848.58 Hz and thresholds in the APD group ranged from 5.96 – 924.37 Hz. These ranges reveal a high degree of variability in the thresholds recorded in the clinical population. The minimum threshold in the range of performance for both clinical diagnostic groups approximates the average discrimination threshold for older, typically developing children and normal adults reported by Jensen and Neff (1993) (6 Hz) and Maxon and Hochberg (1982) (9.5 Hz). Despite the overlap in threshold range, as a group the thresholds from the APD group of children were higher than those from the children in the non-APD group. Mean thresholds were 82.32 Hz and 231.65 Hz for non-APD and APD children respectively. These average discrimination thresholds for both groups are significantly higher than those reported by Jensen and Neff (1993) (6 Hz) and Maxon and Hochberg (1982) (9.5 Hz). Although there is a substantial amount of variability in the frequency discrimination thresholds and fewer listeners at older ages, Figure 5 does appear to show the presence of an improvement (decrease) in threshold and a decrease in threshold variability with increasing age. This pattern within the data, decreasing variability and improvement in threshold, would be consistent with the presence of a developmental trend.

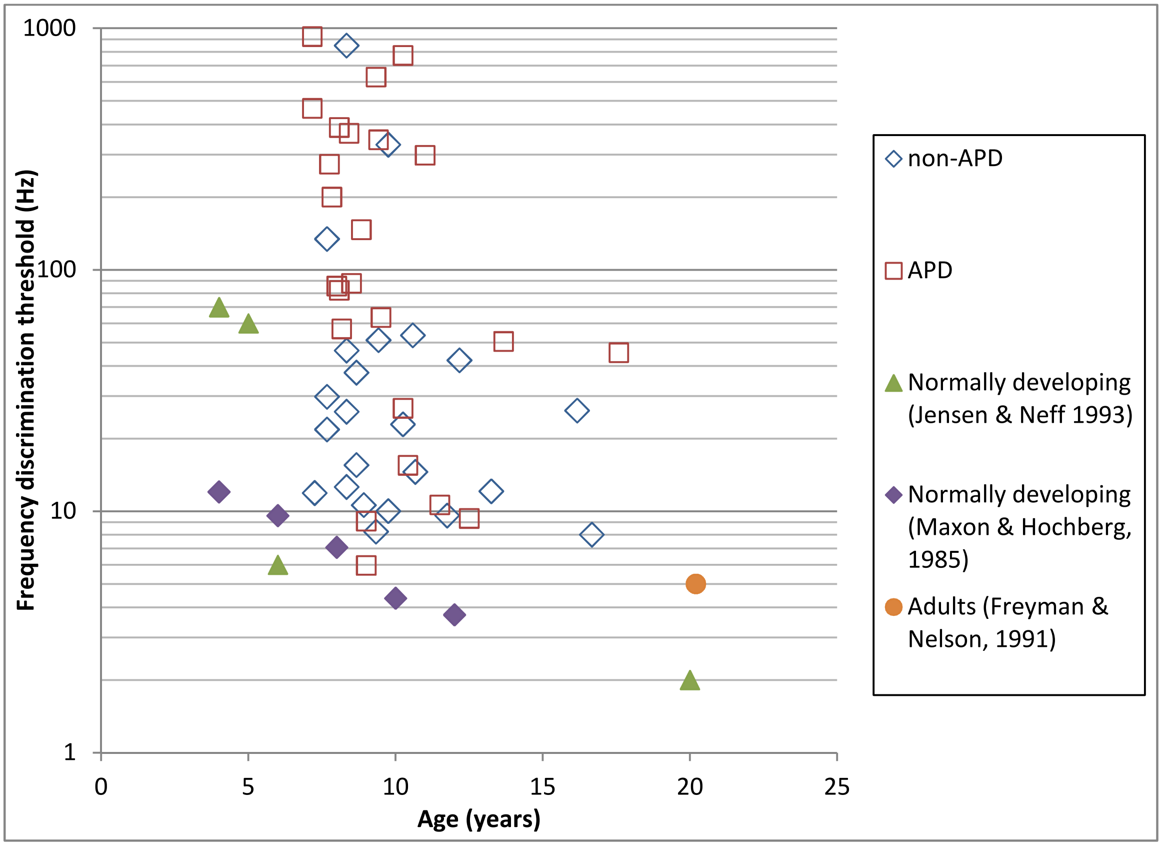


Figure 5 Frequency discrimination thresholds for study participants are displayed as a function of listener age and diagnostic classification. Children diagnosed as APD and those not are represented by the open red square and open blue diamond respectively. Mean thresholds from typically developing children and normal adults as reported in the literature are represented by the solid green triangle (Jensen & Neff, 1993), solid violet diamond, (Maxon & Hochberg, 1985), and solid gold circle (Freyman & Nelson, 1991).

A statistical analysis was undertaken to evaluate the difference in threshold as a function of diagnostic group. A univariate analysis of variance was conducted with the fixed variable auditory processing group. Levene's test of equality of error variances was statistically significant $F(1,45) = 6.638$, $p = 0.013$, revealing that threshold values for the groups did not have equal variance. The ANOVA, corrected model, was statistically significant, $F(1,46) = 5.195$, $p = 0.027$, $\eta^2 = 0.103$ revealing that the differences between groups were significant. Figure 6 shows a plot of the average discrimination thresholds as a function of age and clinical groups. For the purpose of this plot the children were allocated to three groups including 7 to 8 years, 9 to 10 years, and 11 to 17 years with each group having an average age of 8.15 years, 9.84 years, and 13.4 years respectively. The open circles represent mean threshold and the vertical lines represent the standard error for the age group. The children identified as APD and those not are represented by green and blue symbols respectively. Figure 6 shows that the two clinical groups performed differently on the frequency discrimination task. Figure 6 also displays the developmental trend that appeared to be present in the data. Studies of typically developing children, as discussed earlier in the introduction, clearly indicate that there is a developmental trend in the acquisition of frequency discrimination abilities. A correlation between age and discrimination threshold was conducted to determine if what appeared to be a developmental trend observed in the data, as seen in Figures 5 and 6, was significant. The nonparametric correlation between age and discrimination threshold was found to be approaching statistical significance, Spearman's rho $r(45) = -0.361$, $p = 0.013$. This result confirms that the relationship between age and threshold is not linear but that there is an improvement in threshold with increasing age.

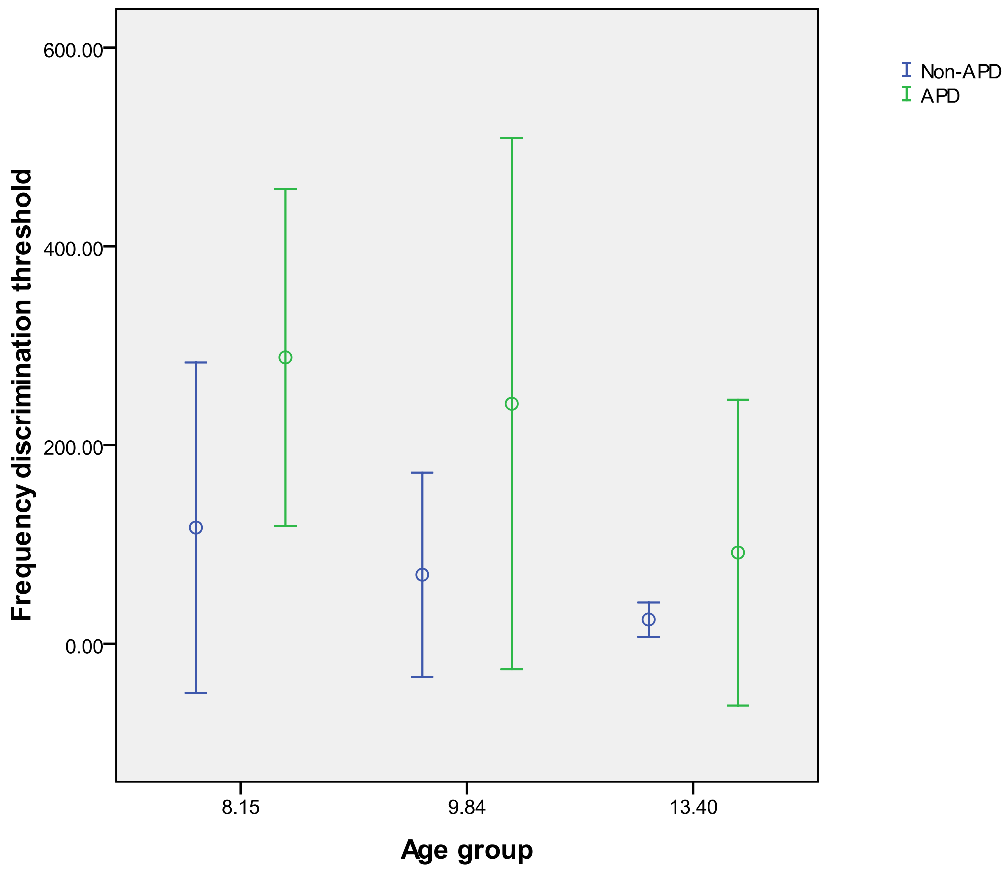


Figure 6 Frequency discrimination thresholds are displayed for the children according to age group and clinical group allocation. Thresholds for the APD group are represented by the green symbols and non-APD by the blue symbols. Circles represent the mean threshold scores and standard error is represented by vertical lines extending from the mean.

3.4 Discussion

The purpose of this study was to examine the frequency discrimination abilities in children suspected of having an auditory processing disorder. Thresholds were estimated at 1000 Hz, the region where the ear is most sensitive. As seen in Figure 5, a large number of children that participated in this study demonstrated elevated thresholds in comparison to the studies conducted by Maxon and Hochberg (1982) and Jensen and Neff (1993) who employed signal parameters that most closely resemble those used in this study. Only twelve or 26% of the forty-seven study participants demonstrated thresholds that fell within 10 dB of threshold values for typically developing children of the same age, as reported by Maxon and Hochberg (1982). The remaining 74% of study participants had elevated frequency discrimination thresholds which included both children identified as APD and those that were not. Frequency discrimination thresholds measured in the group of children diagnosed as APD were significantly poorer and showed greater variability than those who, although representing a group with clinical concerns, were not defined as APD according to the audiologic test battery. This suggests that the children diagnosed as APD are also those most likely to experience the greatest difficulty encoding signal frequency. It is evident, however, from the range of frequency discrimination thresholds in the non-APD group that the absence of a clinical diagnosis does not preclude difficulty encoding signal frequency. The high number of children demonstrating elevated thresholds in this study suggests that within the clinical population, children can often be experiencing compromised frequency discrimination. There also remains the possibility that some of the children demonstrating elevated thresholds on the frequency discrimination task may have shown poor performance as a result of other difficulties that impeded their ability to successfully complete the alternative forced-choice task such as inattention to the task or a misunderstanding of the task.

There was evidence of a developmental trend in the frequency discrimination thresholds collected in this study. This finding is consistent with the results of frequency discrimination thresholds that have been reported in the literature for the pediatric population. Although less than half of the participants in this study demonstrated age-appropriate frequency discrimination thresholds, there was a trend for a decrease in threshold with an increase in listener age. A reduction in the variability of the threshold values was also observed with an increase in listener age. The large variability in the data suggests that in the clinical population, those children with elevated frequency discrimination thresholds include individuals with outlier performance and individuals that achieve thresholds that are similar to younger typically developing children. This finding suggests the presence of both delayed development and disordered frequency discrimination abilities in the clinical population.

Evidence from this study demonstrated that children at risk for an auditory processing disorder may have frequency discrimination problems. Regardless of the clinical designation for participants in this study, the majority of children suspected of having auditory processing deficits were experiencing difficulty discriminating signal frequency. The designation of APD by the traditional clinical test battery does not adequately account for the number of children experiencing difficulty discriminating frequency. It was true for this study that a greater number of children identified as having APD were also identified as having difficulty discriminating frequency. This trend for poor frequency discrimination to be present in children with APD diagnosis may be related to the importance of accurate spectral encoding in the understanding of speech signals. Frequency discrimination difficulties have been reported in children with specific language impairment (Hill, Hogben, & Bishop, 2005; McArthur & Bishop, 2004a, 2000b; Nickisch & Massinger, 2009) and in children that have difficulty recognizing prosodic information (McFadden, 2006). These are both areas that can also be found as co-morbid problems for children identified as APD. Because 74% of the children in the study demonstrated difficulty with frequency discrimination and because the ability to discriminate and understand changes in frequency are so important to language and metalinguistic comprehension, it would appear that the ability to encode spectral information is an important auditory process that should be investigated as part of a test battery. This may be an important diagnostic tool when considering those children that are experiencing auditory disorders and yet are not being identified by tests presently being employed in the traditional clinical setting. The introduction of a tool into the clinic for the assessment of frequency discrimination abilities in children would appear to make an important contribution towards the identification of auditory processing disorders that may be present in the clinical population of children.

Chapter 4

4 Intensity Discrimination

Intensity discrimination threshold or the intensity difference limen refers to the smallest change in the intensity/level of a signal that can be perceived by a listener. Intensity changes in speech are important markers that carry meaning beyond spoken words. Like frequency, the ability to detect changes in intensity is important for understanding prosodic and metalinguistic information contained in speech. For example, when the speaker wants to emphasize a key point they may stress that word or combination of words by way of a slight increase in intensity. Another example observed in speech is the ability to interpret the emotional state of the speaker or the emotional content of their message through the detection of level changes. People typically increase their volume when expressing intense emotion such as excitement, anger or joy. Intensity also provides information for the interpretation of non-speech sounds. Important cues for safety can be carried in the intensity changes that occur in non-speech sound. For example, the ability to discriminate a change in signal intensity can, along with other signal features, inform the listener of the source proximity. Recognizing intensity change as something approaches from behind is an alerting mechanism that is important for ensuring safety from danger. The ability to interpret intensity cues in speech and non-speech sound is dependent on the ability of the listener to discriminate changes in level that can be subtle. The investigation of intensity discrimination is rarely conducted in the audiology clinic even though tools, such as the Short Increment Sensitivity Index (Buus, Florentine & Redden, 1982; Harbert, Young & Weiss, 1969), have been and continue to be available on many diagnostic audiometers. Intensity discrimination has been investigated in the laboratory using a variety of methods.

4.1.1 Intensity discrimination in adults

Laboratory investigations into intensity discrimination generally employ a sequential presentation method. In this method the listener is presented with multiple signals and asked to identify the louder signal. Studies of intensity discrimination abilities in adults have revealed thresholds that are very small, demonstrating that the mature auditory system is very sensitive to level changes in signals. Bacon and Viemeister (1994) reported discrimination thresholds as small as 2 dB using a two interval forced choice procedure for 200 ms 16,000 Hz tones at a presentation level of 40 dB SL. Frequency and intensity discrimination abilities in young adults and aged listeners were investigated by He, Dubno and Mills (1998) for four frequencies at two pedestal presentation levels using a maximum-likelihood method. At a 40 dB SPL presentation level the average intensity discrimination threshold for a 1000 Hz signal was recorded at 2.75 dB $\pm$ 1.39 for the young adults. Small intensity discrimination thresholds and an improvement in threshold with an increase in pedestal base sensation level are commonly reported in investigations with adults but there are inconsistent reports of the degree to which frequency has an effect on the discrimination threshold. Using a sequential signal presentation procedure with adults, Jesteadt, Wier and Green (1977) investigated intensity discrimination for eight different frequencies (200 - 8000 Hz) and 5 different pedestal base levels (5 - 80 SL). Signals were 500 ms in duration. They reported results that indicated intensity discrimination thresholds were independent of signal frequency and that threshold decreased (improved) as a function of increasing pedestal base sensation level. For these adult listeners, the discrimination threshold in a two interval forced choice procedure averaged 3 dB for a 1000Hz signal at a 40 dB SL pedestal presentation level. When they investigated intensity discrimination using masked signals of different frequencies (500 – 8000 Hz) and durations (5 – 70 ms), Carlyon and Moore (1984) found that discrimination thresholds increased with increasing frequency. With intensity held constant at 55 dB SPL they also found that thresholds decreased (improved) with increasing duration up to 60 – 70 ms. For adults listening to 500 Hz signals presented at a 55 dB SPL pedestal level and 70 ms duration, the average discrimination threshold was 1 dB. Florentine (1986) reported that discrimination thresholds in adults decreased with increasing level and increasing duration but that the effect of frequency on discrimination threshold was not significant. The adult listeners' intensity discrimination threshold for 1000 Hz signals with a duration of 500 ms and a pedestal presentation level of 65 dB SPL was 1.5 dB. Florentine, Buus and Mason (1987) further investigated the effects of frequency and level using tones that varied in frequency (250 – 16000 Hz) and level (10 to 95 dB SPL). Signals were 500ms in duration and presented in a two interval forced choice procedure. There was some inter-subject variability but the group of adult listeners demonstrated a decrease (improvement) in intensity discrimination threshold with an increase in level. At higher frequencies the improvement in discrimination threshold was greater than observed in low and mid frequency range. For these adult listeners, the average intensity discrimination threshold for the 500 ms 1000 Hz signal presented at 60 dB SPL was 1.42 dB $\pm$ 1.42.

4.1.2 Intensity discrimination in typically developing children

Children demonstrate a developmental trend in the ability to discriminate intensity. They also demonstrate the same base pedestal level and frequency effects that are observed in adults. Maxon and Hochberg (1982) investigated intensity discrimination ability in children. Discrimination thresholds were obtained for 500, 1000, 2000, and 4000 Hz signals that had a 400 ms duration. The pedestal presentation levels included 10, 20, 40, and 60 dB SL. They found that the children demonstrated a significant reduction in discrimination threshold with increasing frequency and a significant decrease in threshold also occurred with increasing pedestal presentation level. These findings are similar to the effects seen in adults. Although a significant frequency effect was seen in the Maxon and Hochberg (1982) data set, thresholds for frequencies were pooled according to age group. Discrimination threshold was shown to decrease (improve) with increasing age but the biggest effects were seen at low presentation levels. At a pedestal presentation level of 60 dB SL even the youngest age group (4 years) achieved intensity discrimination thresholds that were somewhat similar to those expected for young adults. Range of average intensity discrimination thresholds for children 4 – 12 years were recorded between 2.25 $\pm$ 0.277 and 0.915 $\pm$ 0.304 dB averaged across frequency. In comparison to the Maxon and Hochberg (1982) study, the improvement in intensity discrimination threshold with increasing age was much greater in the sample of children (4 – 6 years) that participated in the study conducted by Jensen and Neff (1993). They had the children and a group of adults discriminating intensity changes in a 440 Hz 400 ms signal with a pedestal presentation level of 70 dB SPL. A significant amount of variability was observed in the children's performance and a significant decrease in threshold was observed with increasing age. The largest influence for this trend was the performance of the youngest age group (4 years). The 4-year-old children's discrimination thresholds averaged 7.5 dB with a range from 2.5 to 12 dB. Thresholds improved and variability decreased with increasing age. The 5-year-old children achieved a mean discrimination threshold of 4 dB and the 6-year-old children performed similar to adults with a mean threshold of 3 dB. The average adult threshold was 1 dB. Narrowband noise bursts centred at 2 frequencies: 400 or 4000 Hz were employed by Berg and Boswell (2000) for a study of intensity discrimination in children 1 – 3 years of age and a group of adults. Stimulus duration was 200 ms and three different pedestal presentation levels (34, 45, 55 dB SPL) were evaluated in a go-no-go procedure performed in soundfield. The children's thresholds were elevated (larger) than those of the adults and there was a significant interaction for age and frequency. Performance was better (lower thresholds) for the 4000 Hz signal when compared to the 400 Hz threshold at the softest pedestal levels. Thresholds decreased (improved) with increasing age and pedestal presentation level. At a pedestal presentation level of 55 dB SPL the intensity discrimination thresholds for the 400 and 4000 Hz signals were similar and the average threshold was 3, 2, and 1.8 dB for the 1, 2 and 3 year olds respectively. Adults also demonstrated similar thresholds for the two signals and were recorded as 0.5 dB.

4.1.3 Summary

Intensity discrimination thresholds in children and adults vary with signal features. The largest effects on threshold have been noted for signal duration and presentation pedestal level (Moore, 2004, Chapter 4; Plack & Carlyon, 1995). Thresholds decrease (improve) with an increase in pedestal level and/or signal duration. An improvement in discrimination thresholds is also observed with increases in signal frequency. The ability to detect sound is not in doubt for children with APD but their ability to discriminate change in signal level remains unknown. Typically developing children appear to have achieved adult performance by 6 years of age. The goal of this study was to investigate the intensity discrimination abilities of children suspected of having an auditory processing deficit. It was hypothesized that most if not all of the children considered part of the clinical population would have age appropriate intensity discrimination ability. This theory was based on behavioural observations and parent report. It is a somewhat common occurrence for parents of young children in the clinical population to report that their child is sensitive to loud sounds such as vacuums and that the children do not enjoy activities that typically involve loud sounds such as a parade or circus (Keith, 1999). They also report that the children do not typically have difficulty recognizing changes in emotion that are frequently associated with raised voices (increased level) such as anger or excitement. The one caveat to the belief that the clinical population may not have difficulty encoding signal intensity relates to anecdotal parental reports of these children misunderstanding information because they did not recognize stressed words in a sentence. Although it is not the only mechanism available to relay stress or emphasis on words in a sentence, one of the means through which stress can be indicated is an increase of intensity on the words that contain the important information. The report of the inability of some children in the clinical population to recognize information that has been emphasized leads to the possibility that children in a sample of the clinical population may have difficulty discriminating small changes in intensity.

4.2 Method

This study of intensity discrimination in the clinical population adheres to the General Method as described in Chapter 2. This method section describes the study participants as well as the signal parameters and procedures that are unique to the intensity discrimination study.

4.2.1 Participants

Twenty-one children, 5 girls (7 – 12 years) and 16 boys (7 – 17 years), participated in the study of intensity discrimination. All children were part of a clinical population that presented with some level of academic failure and were demonstrating behaviour that suggested the presence of an auditory processing disorder. A clinical assessment of auditory processing was conducted with these children as described in the general method and according to their scores on the clinical test battery, 11 children qualified for an APD diagnosis and 10 children were considered non-APD

4.2.2 Signals & Procedure

The signals were 500 ms samples of 1000 Hz pure tones. Signals were passed through a cosine squared gating filter with a 10 ms ramp size. The standard stimuli were presented at 57 dB SPL. The target level varied adaptively, with an initial starting level of 72 dB SPL. Level changed with each reversal according to the 2-down, 1-up procedure. The initial step size was 8 dB SPL, which occurred after two consecutive correct responses, or one incorrect response. Each subsequent reversal resulted in an increase or decrease of the target signal intensity by a factor of 0.5. The final step size for this task was 2 dB SPL. All signals were separated by a 450 ms inter-stimulus interval.

4.3 Results

All 21 children completed three 30-trial blocks of the intensity discrimination test. Thresholds were calculated for each block. Minimum requirements and threshold calculation was achieved as described in the general method. A repeated measures analysis of variance was conducted for the three blocks of trials. A statistically significant difference was not found between the three blocks of trials, Pillai's Trace = 0.082, $F(2,19) = 0.846$, $p = 0.445$, $\eta^2 = 0.082$. Because there was no significant difference between trial blocks, the three threshold estimates were averaged to produce a single discrimination threshold estimate. Figure 7 shows the intensity discrimination thresholds for all listeners plotted as a function of age. Thresholds for the clinical groups are denoted by the open blue diamond and open red square symbols for the non-APD and APD listeners, respectively. For comparison, thresholds from previously published studies using somewhat similar signal features and age groups have been included in the figure. They are shown by the filled green triangles (Maxon & Hochberg, 1982), filled violet diamonds (Jensen & Neff, 1993), filled red circle (He, Dubno & Mills, 1998), and filled orange circles (Berg & Boswell, 2000), and represent means for the age groups at which they are plotted.

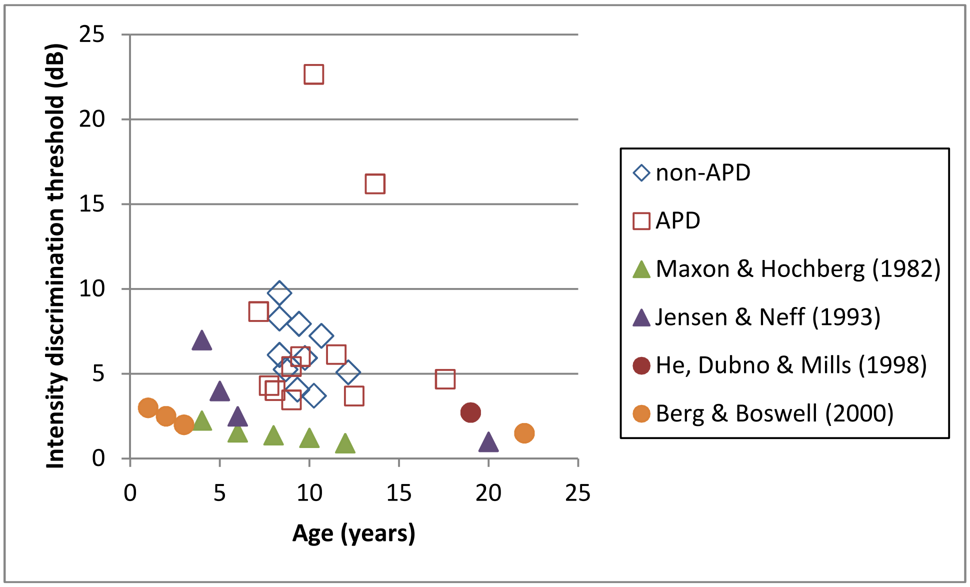


Figure 7 Intensity discrimination thresholds are shown as a function of listener age and diagnostic group. Individual thresholds for the children classified as APD and those that are not are shown by the open red squares and open blue diamonds, respectively. Mean thresholds from typically developing children, as reported in the literature are shown by the filled violet diamonds (Jensen & Neff, 1993), filled red circle (He, Dubno, & Mills, 1998), and the filled orange circles (Berg & Boswell, 2000).

Mean threshold for the non-APD group was 6.34 dB and for the APD group was 7.75 dB. Variance was larger in the APD group (SD = 6.13 dB) than the non-APD group (SD = 1.94 dB). Variability in the APD group was largely influenced by the performance of two children whose data were outliers as can be seen in Figure 7. If the two outliers are removed from the data set the APD group intensity discrimination thresholds decrease to a mean of 5.16 dB with a standard deviation of 1.64 dB. Figure 7 shows that the children participating in this study had intensity discrimination thresholds that were higher than expected when compared to the findings of He et al. (1998), Maxon and Hochberg (1982), and Jensen and Neff (1993). Most children demonstrating elevated thresholds were only a few dB higher than the published findings. However, there were two children that had elevated thresholds. The two outlier thresholds belong to children that were identified as APD as seen in Figure 7.

A univariate analysis of variance was conducted to evaluate the relationship between the dependant variable intensity discrimination threshold and the independent variable clinical behaviour-based diagnosis which had two levels, APD and non-APD designation. The ANOVA was conducted with the entire sample of 21 children which included outliers. The Levene Statistic, a test of homogeneity of variances revealed that the difference in variance between the two groups was statistically significant $F(1,19) = 4.719$, $p = 0.043$. Results from the comparison of the intensity discrimination thresholds achieved by the APD and non-APD groups of children revealed that there was no statistically significant difference between the intensity discrimination thresholds achieved by the two groups, $F(1, 19) = 0.485$, $p = 0.495$, $\eta^2 = 0.025$.

4.4 Discussion

The purpose of this study was to investigate intensity discrimination abilities in a group of children with learning and academic problems, who were suspected of having an auditory processing deficit. In the group of 21 children participating in the study, 11 were identified as having an APD based upon behavioral clinical tests and recommended clinical guidelines. The remaining 10 children, who were having difficulties as reported by their caregivers and teachers, were not classified as APD. The discrimination task involved the children listening to 3 samples of a 1000Hz tone, one of which had an intensity increment relative to the others. Each child completed 3 blocks of 30 trials, each of which produced a threshold estimate. The 3 estimates were averaged when no repetition effect was found. Only two children that participated in the study had intensity discrimination thresholds that were elevated to the point where they were considered outliers.

Thresholds were compared to reported data for typically developing children by way of a scatter plot (Figure 7). Intensity discrimination thresholds were not as small as those recorded by He et al. (1998), Maxon and Hochberg, (1982) and Jensen and Neff (1993) but they were only a few dB higher than the published intensity discrimination values for school-aged children. This finding suggested that the children in this sample of the clinical population develop intensity discrimination ability as do children in the normal population. There were, however, two outliers in this sample of children that appeared to have difficulty discriminating intensity or were unable to understand the task. When these two outliers are removed from the sample, the intensity discrimination threshold values achieved by the children in this study had a relatively small variance that was similar across the groups and similar to the normal population. Because the range of intensity discrimination thresholds for this sample of children is relatively small and only two outlying thresholds are present in the group it would appear that the ability to discriminate intensity is not a significant problem for children in this clinical population.

Discrimination thresholds were compared for the children with and without an APD diagnosis. Results showed no statistical difference between the intensity discrimination thresholds obtained by children in the two groups. These results suggest that intensity discrimination is not an area in which signal encoding is a problem for children suspected of having an auditory processing deficit regardless of whether they achieve a clinical diagnosis of APD. The implications of the normal performance demonstrated by the listeners in this study is that these children have the ability to detect small changes in intensity that are critical for recognizing meta-linguistic markers such as stressed words in sentences. They will also be able to recognize changes in nonverbal sounds that may be important cues for safety such as the realization that something is approaching from behind.

Of interest are the two children that performed poorly on the intensity discrimination task. To ascertain if there was some potential clinical significance in the outlying performance on this task, an investigation into the trial-by-trial performance of these children was undertaken. Moore et al. (2008) reported that the review of trial by trial tracking of the target stimulus by a listener can differentiate between the good listener, the genuine poor signal encoder and the inattentive listener. The benefit of this kind of data review is that the inattentive listeners can be redirected into more appropriate assessment and intervention streams while the genuinely poor performer can be further assessed and supported with appropriate habilitation options. For the adaptive procedure and forced choice method employed in this study, a good listener would demonstrate threshold tracking that quickly approached threshold and then responses would have remained close to threshold as the search continued to narrow with ongoing trials. The genuinely poor performer would have a similar threshold search but the threshold value would be elevated in comparison to expected performance. The inattentive listener would demonstrate an erratic threshold search. The threshold tracking would not be systematic, have a large range and would appear to have no focus or narrowing toward a threshold centred search.

The trial-by-trial data for the two intensity discrimination outlying performers are shown in Figure 8 and 9. The outlying performance on the intensity discrimination task is displayed for the 10-year-old and 13-year-old participants in Figures 8 and 9 respectively. Listener responses (target signal level – standard signal level) are shown for each trial. In the adaptive forced choice procedure each incorrect response resulted in an increase in signal level. One correct choice resulted in no change in signal level. Two correct choices in a row resulted in a decrease in level. For both figures, the three trial blocks are shown in order of completion, Block 1 responses are represented by the blue diamonds; Block 2 responses are represented by the red squares, and Block 3 responses are represented by the green triangles. The listener tracking shown in Figure 8 is somewhat erratic and does not display a threshold centred search. There is no consistency across the three trial blocks. This search would be considered representative of an inattentive listener. The tracking performance shown in Figure 9 displays reduced attention to the listening task during Block 3. It can be seen that Block 3 was the primary contribution to the outlier performance. Performance on Block 1 demonstrated attentive listening with a trend towards normal, age appropriate, thresholds. This analysis of trial-by-trial data revealed that the outlier performance on the intensity discrimination task appears related to inattention. What is important about this finding is that it may be possible to use trial-by-trial data as a metric for inattention as a contributing factor to the overall clinical presentation. There continues to be the need to further investigate intensity discrimination in the clinical population but if children, including those that have poor signal encoding for other acoustic features, demonstrate age appropriate intensity discrimination abilities then this test may have significant clinical utility. If psychoacoustic test methods are adopted as a clinical assessment tool, it might also be possible to use intensity discrimination as a clinical control measure during a screening test of signal encoding ability.

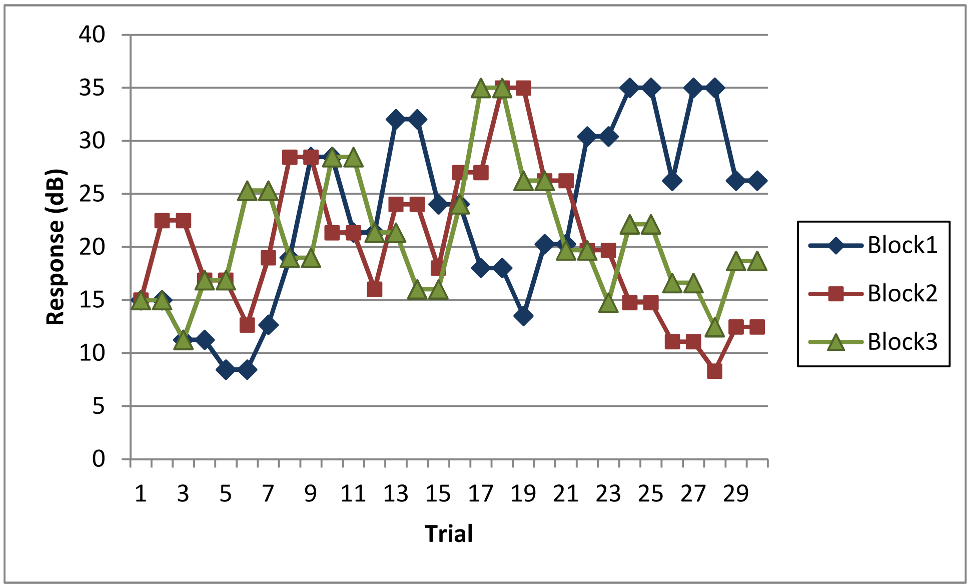


Figure 8 Trial-by-trial responses are shown for three blocks of trials completed by a 10-year-old listener that achieved an outlying intensity discrimination threshold. Responses are plotted as the difference between the target signal level and the standard signal level (target signal level – standard signal level) for each trial in the block. Responses for trial blocks 1, 2, and 3 are represented by the blue diamonds, red squares, and green triangles respectively.

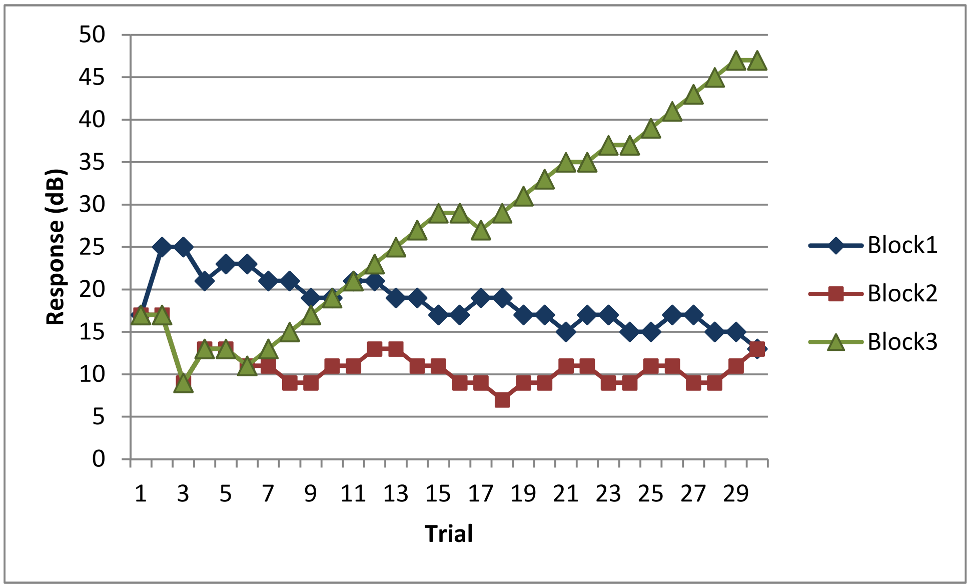


Figure 9 Responses are shown for three blocks of trials completed by a 13-year-old listener that achieved an outlying intensity discrimination threshold. Responses are plotted as the difference between the target signal level and the standard signal level (target signal level – standard signal level) for each trial in the block. Responses for trial blocks 1, 2, and 3 are represented by the blue diamonds, red squares, and green triangles respectively.

Chapter 5

5 Frequency Resolution

Frequency resolution refers to our ability to analyze the frequency composition of sound. For complex signals, the accurate representation of frequency in the auditory system is critical for identification and recognition.

> If we could not determine the frequency content of sound, speech would be Morse code and music would be drum beats. (Yost, 1993 p. 4)

5.1.1 Frequency resolution in adults

The ear can be modeled to behave like a set of overlapping bandpass filters that operate in parallel to detect the frequency components of complex signals (Swets, Green, & Tanner, 1988). These filters are modeled to have a specific width and shape that individually and as a whole dictate the resolving power of the auditory system. Narrower filters would produce a better internal representation of the signal than wider filters. Fletcher (1940) conducted pioneering work in this area when he demonstrated that increases in the bandwidth of a masker would cease to produce an additional masking effect on a tonal signal when the bandwidth exceeded a certain width. Only a specific frequency range of energy was necessary to mask a tone and this bandwidth, known as the critical bandwidth or critical band, varies with frequency. The size of the critical band grows with increasing frequency. At frequencies 500, 1000, 2500 and 4000 Hz the bandwidth is approximately 110, 160, 380, and 700 Hz, respectively (Scharf, 1970). The detailed size/shape of the hypothesized auditory filters and thus the frequency resolving ability or selectivity of the auditory system has been investigated extensively and is loosely related to the critical bandwidth. There are several methods for estimating auditory filter shape and width and include, for example, the psychophysical tuning curve (Greenberg & Larkin, 1968; Hall & Fernandes, 1983; Schafer, Gales, Shewmaker, & Thompson, 1950; Zwicker, 1974) and the notched noise masker procedure (Moore, 1995; Patterson, 1976). The psychophysical tuning curve method typically involves the detection of a fixed-level signal, in the presence of a masking noise. Masker frequency is varied and the minimum masking levels at each masker frequency are used to map the shape of the auditory filter. The psychophysical tuning curve method has been successfully used to map auditory filter shape in adults and in infants (Olsho, 1985; Scharf, 1970). Considerable time is required to acquire an approximation of the tuning curve (Bull, Schneider, & Trehub, 1981; Schneider, Morrongiello, & Trehub, 1990; Schneider, Trehub, Morrongiello & Thorpe, 1989).

The notched noise procedure also requires a listener to detect a signal in the presence of a noise masker. The masker is a broadband noise containing a spectral notch often centred at the frequency of the signal. The size of the spectral notch is systematically varied so that the filter shape can be estimated (Patterson, 1976). Theoretically, when attempting to detect the tone in noise, only the energy that enters the auditory filter would mask the tone. Thus, estimating the rate of change in threshold as the notch width is varied provides an estimate of filter bandwidth. A rapid improvement in threshold when the notch is increased in bandwidth suggests a narrower filter. Varying the placement of the notch with regard to the signal allows an estimate of filter shape. Patterson's (1976) results with adult listeners showed that for 500, 1000, and 2000 Hz the auditory filters had similar shapes, which he modeled as a rounded exponential. The 2000 Hz filter shape was found to have a slightly sharper shape, i.e. more narrowly tuned, than the lower two frequencies tested. The average 3 dB bandwidth at 500, 1000, and 2000 Hz was 69.2, 140, and 207 Hz respectively. Patterson (1976) noted the presence of individual variability in observer performance and indicated that this variability can be quantified as a ratio of the measurement mean to standard deviation. The observed variability in average performance is a reflection of the processing efficiency within the individual listeners. Patterson demonstrated that for the adult listeners included in his study, the adjustments and refitting of functions that were made to account for the variability in processing efficiency of the listeners did not substantially change the filter shape or the filter range to bandwidth relationship.

Patterson (1976) noted that frequency resolution as estimated using a flat and notch noise method must be modeled with two parameters, one that reflects frequency selectivity (or filter bandwidth) and one that reflects processing efficiency. Efficiency refers to the overall signal-to-noise ratio at which detection occurs and is independent of the filter bandwidth. If the auditory system has good frequency resolution but otherwise has reduced efficiency then the tone thresholds in both flat and notched noise masking conditions should be elevated because the impaired processing efficiency has similar effects on both conditions. In contrast, the difference threshold comparing thresholds in flat and notched conditions is more related to filter bandwidth and is not affected by efficiency. In the case of a wider filter bandwidth estimate (suggesting poor frequency resolution) the difference thresholds between the flat and notch masker will be reduced due to a lack of improvement in detection with an introduction of a spectral notch in the masker.

5.1.2 Frequency resolution in typically developing children

Initial examinations of children's frequency resolution abilities using the notched noise method have been completed and suggest that young children may have wider auditory filters than adults. Irwin, Stillman, and Schade, (1986) examined the width of the auditory filter at three signal frequencies, 500, 1000, and 3000 Hz in children 6 and 10 years of age and a group of adults. They acquired thresholds in the no-notch masking condition and five notched noise conditions ranging in relative notch width, defined as $\Delta f/f$, from 0.1 to 0.4 for a total of 6 listening conditions. Data suggested that the 6 year old children had wider auditory filters, as evidenced by a slower improvement in threshold with increasing notch width, and poorer processing efficiency than the 10 year olds and adults. The authors suggest that the wider auditory filters and poorer processing efficiency in younger children could have the practical consequence of poorer understanding of speech in noise.

A flat and notched noise masking method to investigate frequency resolution abilities was also employed by Allen, Wightman, Kistler, and Dolan (1989) in children ages 3 to 9 years of age and a group of adults. Thresholds were obtained for 500, 2000, and 4000 Hz pure tones in two masking conditions. In one condition the Gaussian noise masker spectrum was flat and centred at the signal frequency. In the other condition the masker was composed of two noise bands, one placed on each side of the signal frequency, forming the notched masking condition. The maskers were set to 40 dB SPL spectrum level in both masking conditions. Thresholds for the children, regardless of the masking condition were found to be higher than those of the adults confirming earlier suggestions of poorer processing efficiency in young children. As well, the difference in thresholds in the flat and notched masker increased with age suggesting age related changes in filter width. By 6 years of age the children had achieved adult performance levels. The difference threshold observed for the older children and adults across frequency had an estimated range of 10 – 18 dB. The developmental trend observed by Allen et al. (1989), was similar to the results obtained by Irwin et al. (1986) and suggested that young children have reduced frequency resolution abilities but that by 5 or 6 years of age frequency resolution is similar to adults.

Allen et al. (1989) noted a high degree of intra-subject variability in the children's performance. The authors postulate that this may be related to immature attention and/or poor concentration. The acquisition of adult-like temporal resolution abilities by the age of 6 years was seen in a study conducted by Veloso, Hall, and Grose (1990). A 1000 Hz tone test frequency in flat and notched broadband noise conditions was employed. Masker bandwidth was 1400 Hz centred at the test frequency. Three listening conditions included a no-notch (0 Hz) condition and 300 and 600 Hz wide notch conditions. To create the notch, the masker was divided into two 700 Hz bands, one on either side of the test frequency. The presentation of the maskers was set at 40 dB SPL spectrum level. Average threshold differences in the notched and flat conditions for the 1000Hz signal in a masker with a 300 Hz bandwidth were 15 dB in adults and 16 dB in the children. This is similar to the Allen et al. (1989) finding of adult level performance in 6 year old children.

With evidence of adult-level frequency resolution in children as young as 6 years on a flat and notched noise test method, Hall and Grose (1991) investigated frequency resolution in young children, 4 to 6 years of age and a group of adults. Test frequencies were 500 and 2000 Hz. Three masking conditions were tested. In the flat noise condition a noise band was used that had a width of 1.4 times the centre frequency. The flat noise was centred at the test frequency. The other two masking conditions used two bands of noise having a width of 0.7 times the test signal frequency located symmetrically above and below the test signal frequency. Notch width was 0.3 times the centre frequency in one notch noise test condition and 0.6 times the centre frequency in the other. Similar to the Allen et al. (1989) findings, the 6 year old children performed in a similar way to the adults in the Hall and Grose (1991) study. Masked thresholds were found to be elevated in the 4 year old children when compared to the adult thresholds. Differences between thresholds obtained across age groups in the notched (0.3 times the centre frequency condition) and flat noise masker ranged from 13 – 17 dB and are comparable to the difference thresholds observed in the Allen et al. (1989) study. The differences in thresholds were somewhat larger for the wider notch noise condition (20 - 32 dB). Hall and Grose (1991), in confirming the reduced abilities of younger children on this task, suggested that the younger children do experience a perceptual disadvantage but that it remains unclear whether this is the result of poor frequency resolution or processing efficiency.

5.1.3 Summary

In summary, there is significant variability in the performance of young children on tests of frequency resolution that use a notched-noise masking procedure. However, most typically developing children demonstrate adult-like performance on frequency resolving tasks by 6 years of age. It has been theorized that children with wider auditory filters and/or poor processing efficiency may experience difficulty understanding speech in noisy listening conditions due to poor frequency resolving abilities. Because teachers and parents often report that children with auditory processing disorder have difficulty listening when it is noisy, the possibility of a disturbance in the frequency resolving abilities of these children is plausible. Recently, Moore et al. (2010) assessed a group of randomly selected 6 to 11 year old children attending typical elementary level classrooms on a number of tests including frequency resolution. The notched noise procedure was used to assess frequency resolution at 1000 Hz. The 1000 Hz tone was presented in a bandpass noise masker with and without an 800-1200 Hz spectral notch. Thresholds were obtained in the flat noise and the notched noise conditions. They found a high degree of variability in both the flat and notched noise condition thresholds. A decrease in threshold was observed with age but the median difference threshold, used as an estimate of frequency resolution, changed little as a function of age and was similar to the report of normal adult and child thresholds reported by the same research group in 2011 (Moore, Cowan, Riley, Edmondson-Jones, & Ferguson, 2011). Further analysis of the 2010 study results was conducted to investigate the poorest performance on each of the auditory tasks included in the study. The results of this further analysis showed that the poorest auditory processing performers did demonstrate poorer frequency resolution than expected.

5.2 Method

The frequency resolution study adheres to the General Method as described in Chapter 2. This study-specific method section describes the participants as well as the signal parameters and procedures that were unique to the frequency resolution study.

5.2.1 Participants

Twenty-three children, six girls (7 – 13 years) and seventeen boys (7 – 17 years) participated in the study. All the children participated in the larger study investigating auditory processing abilities in children. The clinical classification of children into APD and non-APD groups resulted in seventeen of the children classified as APD according to the clinical test battery and six were not (based upon 2 or more of the 5 behavioral tests of central auditory function falling more than 2 standard deviations below expectations). All had normal hearing sensitivity as described in the general method.

5.2.2 Signals & Procedure

The signal to be detected was a 390 ms sample of a 1000 Hz pure tone. This signal was presented in two masked conditions. In one condition the masker was a 390 ms sample of Gaussian noise that was low pass filtered with a cut-off frequency of 2000 Hz. The masker was played at 40 dB SPL spectrum level. In the second condition the masker was a 390 ms sample of Gaussian noise that was low pass filtered with a cut-off frequency of 2200 Hz that was bandstop filtered to produce a 400 Hz wide spectral notch centered at 1000 Hz. Masker spectrum level outside of the notch was 40 dB SPL.

All signals were passed through 10 ms cosine squared gating on and off ramps. Signals were generated as described in the general method. In the adaptive 3AFC task the listeners were asked to select which of the three masker samples also contained the pure tone signal. For both flat and notched masker conditions, the signal was initially presented at 72 dB SPL. Signal level was then changed according to a 2-down, 1-up procedure thus tracking the 70.7% correct level. Level changed by 8 dB until the first reversal was reached when the change was reduced by a factor of 0.5 following each reversal until the final step size of 2 dB was reached. Listeners completed 3 blocks of 30 trials in each of the two masker conditions.

5.3 Results

All twenty three children completed the six 30-trial blocks, three trial blocks in each of the flat and notched noise conditions. Thresholds were calculated after each block of trials. A repeated measures analysis of variance was conducted with the three block thresholds in each condition. A statistically significant difference between individual block thresholds was not found for either the flat noise condition, Pillai's Trace = 0.111, $F(2,21) = 1.314$, $p = 0.290$, $\eta^2 = 0.111$, or notched noise condition Pillai's Trace = 0.019, $F(2,21) = 0.201$, $p = 0.820$, $\eta^2 = 0.019$. The three threshold estimates in each condition were therefore averaged. Estimates of frequency resolution were obtained by comparing the average thresholds obtained in the notched and flat masker conditions.

Performance in the flat noise condition is shown in Figure 10. Average thresholds in the flat spectrum masker condition for all listeners are plotted as a function of listener age. Clinical groups are denoted by the open blue diamond and open red square symbols for the non-APD and APD listeners, respectively. For comparison, thresholds from previously published studies using similar signal features and age groups have been included in the figure. They are shown by the filled green triangles (Allen et al., 1989), filled violet diamonds (Veloso et al., 1990), and filled red circles (Hall & Grose, 1991) and represent means for the age groups at which they are plotted. Also included in the plot, represented by the filled blue circle symbols, are mean masked detection thresholds for children and adults as reported by Allen and Wightman (1994). As can be seen in

Figure 10, flat noise thresholds estimated for the APD and non-APD children were similar to those reported previously for similarly aged children and the groups also showed similar performance. Mean threshold for the non-APD children was 62.53 dB SPL (SD = 1.69). Mean threshold for the APD group was 64.19 dB SPL (SD = 3.95).

Performance in the notch noise condition is shown in Figure 11. Average thresholds in the notched noise condition for all listeners are plotted as a function of listener age. Data from the children diagnosed with APD and those not are shown by the open red square and open blue diamond symbols, respectively. As in Figure 10, average thresholds reported in previous studies have been included in the figure and are shown by the filled green triangles (Allen et al., 1989), filled violet diamonds (Veloso et al., 1990), and filled red circles (Hall & Grose, 1991) and represent means for the age groups at which they are plotted. It can be seen in Figure 11 that the thresholds obtained from both the APD and non-APD children are elevated relative to those published for typically developing children and are more similar to thresholds reported for younger children. The mean threshold for the non-APD group was 54.87 dB SPL (SD = 2.27). The APD mean threshold was 59.21 dB SPL (SD = 4.71). Significant overlap between individual thresholds in the APD and non-APD groups can be seen in Figure 10 and 11 but many of the children in the APD group showed elevated thresholds when compared to those in the non-APD group in the notch noise condition (Figure 11).

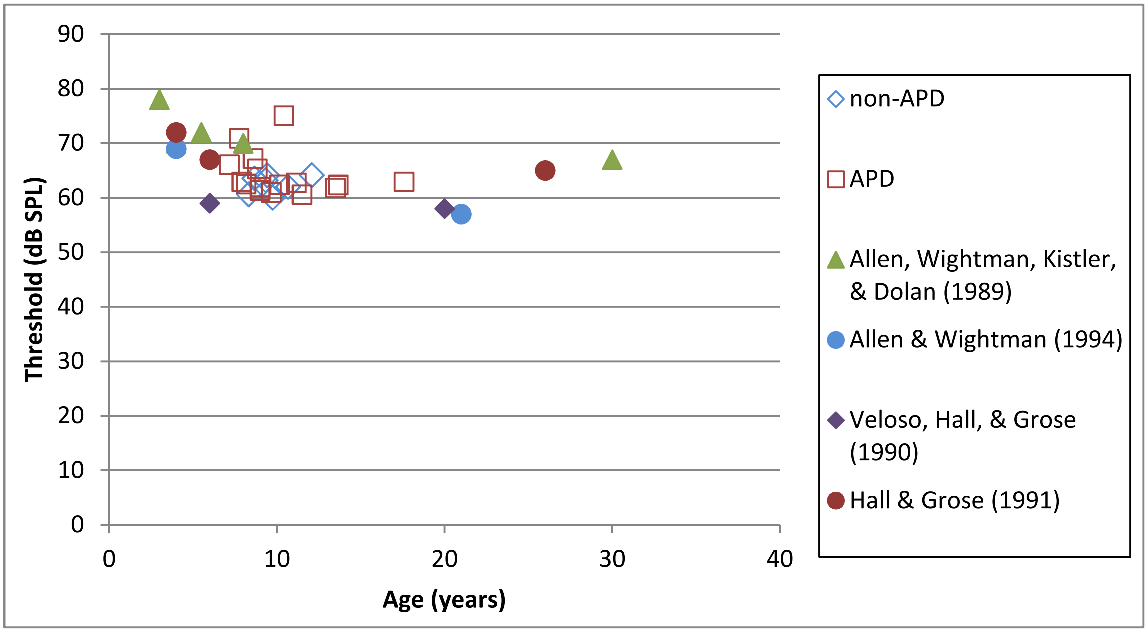


Figure 10 Thresholds for the flat noise condition are shown as a function of age and diagnostic group. Individual thresholds for the children classified as APD and those not are shown by the open squares and diamonds, respectively. Mean thresholds from typically developing children reported in the literature are shown by the filled symbols.

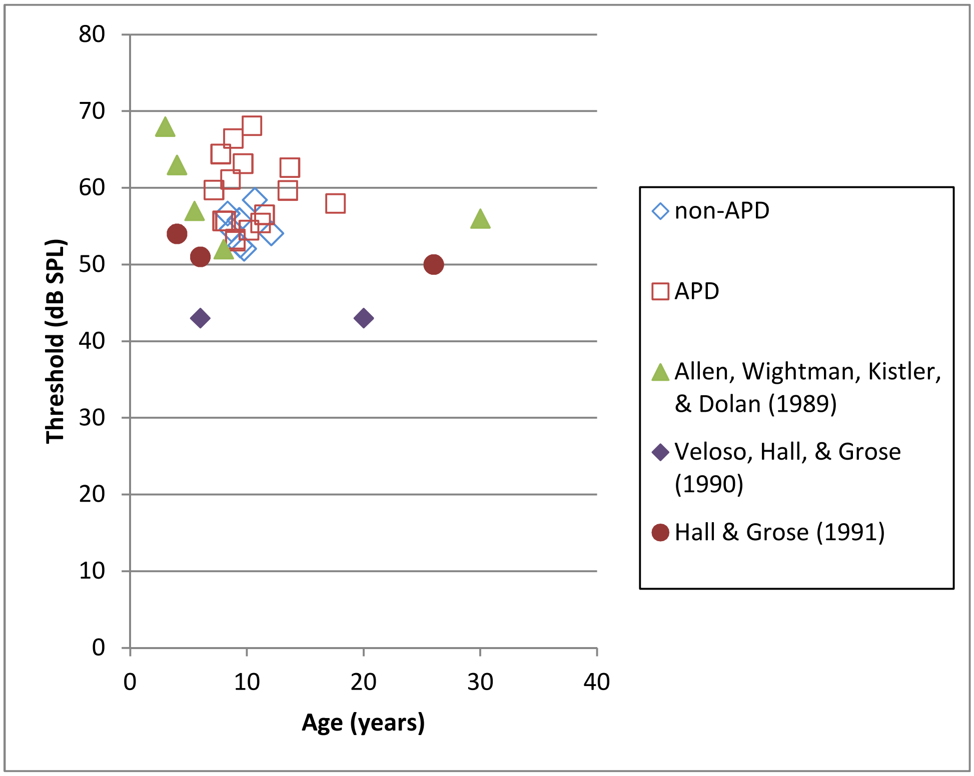


Figure 11 Thresholds for the notch noise condition are shown as a function of age and diagnostic group. Individual thresholds for the children classified as APD and those not are shown by the open squares and diamonds, respectively. Mean thresholds from typically developing children reported in the literature are shown by the filled symbols.

A multivariate analysis of variance was conducted to determine if there were statistically significant differences in the thresholds achieved in the two masking conditions by the two groups of children. Levene's test for equality of error variances for the APD and non-APD groups was not statistically significant in the flat noise condition, $F(1,21) = 1.903$, $p = 0.182$, but was statistically significant in the notch noise condition $F(1,21) = 4.625$, $p = 0.043$. These results suggest homogeneity of variance in thresholds obtained in the APD and non-APD groups in the flat noise condition but not in the notched noise condition. This finding would be a reflection of the trend towards higher thresholds achieved in the notched noise condition for the APD group as seen in Figure 11. The multivariate analysis of variance was conducted with the independent variable being group designation and the dependant variables being tone in noise thresholds. Results of the analysis revealed the absence of statistically significant differences between groups, Pillai's Trace = 0.126, $F(2,20) = 1.445$, $p = 0.259$, $\eta^2 = 0.126$. The difference in the flat noise threshold values achieved by the APD and non-APD children was not statistically significant, $F(1,21) = 0.747$, $p = 0.397$, $\eta^2 = 0.034$. The difference in the notched noise threshold values achieved by the APD and non-APD groups was not statistically significant $F(1,21) = 2.898$, $p = 0.103$, $\eta^2 = 0.121$.

Figure 12 shows average differences in thresholds between the flat and notched noise conditions plotted for all listeners as a function of listener age and clinical group. The open blue diamond and the open red square symbols represent the non-APD and APD groups respectively. Difference thresholds from previous studies are shown by the filled green triangle (Allen et al., 1989), filled violet diamond (Veloso et al., 1990), and filled red circle (Hall & Grose, 1991) symbols. It is evident that the difference thresholds in both the APD and non-APD groups are smaller in comparison to those reported for typically developing children of similar age. The mean difference threshold for the non-APD and APD groups was 7.26 dB SPL (SD = 3.06) and 5.16 dB SPL (SD = 3.56) respectively. Paired samples t-tests were conducted to determine if the change in threshold observed between the flat noise condition and the notched noise condition was statistically significant for the two clinical groups. The change in threshold from the flat noise condition to the notched noise conditions, was statistically significant in the APD,

$t(16) = 5.964$, $p < 0.001$ and non-APD, $t(5) = 5.815$, $p = 0.002$, groups. An independent samples t-test revealed that there was no statistically significant difference between the difference thresholds obtained by the two groups, $t(21) = 1.285$, $p = 0.213$. These results suggest that the APD and non-APD children have similar frequency resolving ability as estimated by the tone-in-noise masking method and that both groups show diminished frequency resolution ability when compared to typically developing children of similar ages.

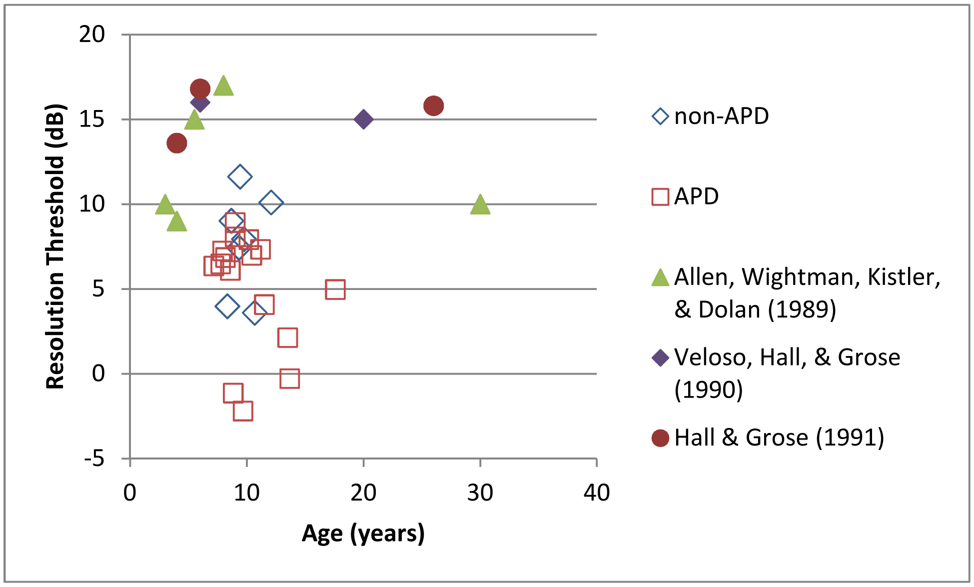


Figure 12 Frequency Resolution thresholds (flat noise threshold – notch noise threshold) are shown as a function of age and diagnostic group. Individual thresholds for the children classified as APD and those not are shown by the open squares and diamonds, respectively. Mean thresholds from typically developing children reported in the literature are shown by the filled symbols.

5.4 Discussion

The purpose of this study was to investigate frequency resolution abilities in the clinical population of children with learning and academic problems, who were suspected of having an auditory processing deficit. This was accomplished through the evaluation of tone in noise detection thresholds with a sample of 23 children from the clinical population, 17 of whom were identified as suffering from an APD based upon behavioral clinical tests and recommended clinical guidelines. The remaining 6 children, who were having difficulties as reported by their caregivers and teachers, were not classified as APD. The discrimination task involved the children listening to 3 samples noise, one of which contained a 1000 Hz tone centred in the noise signal. There were two signal conditions, one in which the noise had a flat spectrum and in the other condition the noise had a spectral notch that was centred at the tone frequency. Each child completed 3 blocks of 30 trials, for both signal conditions, for a total of 6 blocks. Each block of trials produced a threshold estimate. The 3 estimates for each condition were averaged when no repetition effect was found to achieve two thresholds, one for the flat noise and one for the notched noise condition. In the flat noise condition thresholds for the non-APD and APD groups were not significantly different and both were similar to results reported for typically developing children (Allen & Wightman, 1994; Veloso et al., 1990). In the notched noise condition, thresholds were not significantly different between the APD and non-APD groups, but both groups tended to show higher thresholds (i.e. less improvement in threshold with the addition of the spectral notch) when compared to previously published data from typically developing children. Interestingly, the performance of the children classified as APD was not significantly poorer than that of the non-APD children in the flat and notched noise conditions but it is worth noting that the variance in the APD group thresholds was greater suggesting larger individual differences in the APD group.

Only two participants included in the study, both from the non-APD group, demonstrated frequency resolution estimates that were similar to those described by

Allen et al. (1989) and Hall and Grose (1991) in the typically developing population. There were eight children, two participants in the non-APD group and six in the APD group, who achieved difference thresholds of 5 dB or less. For these listeners, this finding is an indication that the insertion of a spectral notch into the masking noise provided little to no advantage in the signal detection task. One conclusion that can be drawn from the high incidence of children in this study that demonstrated poor frequency resolving abilities is that the assessment battery used to identify the presence or absence of auditory processing disorder was not sufficiently sensitive to distinguish between those children with and without age appropriate frequency resolving ability. Because only two of the children in the non-APD group were found to have frequency resolving abilities that were close to age expectations, the second conclusion that can be made is that poor frequency resolving ability exists in both clinical groups. These children may have wider auditory filter or attention bands, in comparison to the typically developing children. There is evidence to suggest that poor frequency resolving ability is related to difficulty discriminating speech both in quiet and noise for individuals with and without hearing loss (Badri, Siegel, & Wright, 2011; Schorn & Zwicker, 1990). For children suspected of having an auditory processing disorder, one of the common complaints is difficulty listening in noise. It is possible that for these children the listening problems they report experiencing in noise are, at least in part due to poor frequency resolving abilities.

It will be important, however, to determine whether the poor performance in the notch noise condition is the result of auditory filter width, poor processing efficiency (Hall & Grose, 1991; Patterson, 1976), or a combination of the two. In the case of the notched noise frequency resolution task, processing efficiency relates to factors other than the physical size of the auditory filter, such as understanding the task and attention to the signal features. The ability to distinguish between poor performance due to wide auditory filters or poor processing efficiency will be crucial in regards to the possible use of this test as a diagnostic tool and any potential intervention or the treatment approach that would best address the difficulties experienced by the child. The degree to which frequency resolution ability or processing efficiency contributes to the results of the present experiment cannot be ascertained with any degree of certainty. In comparison to published reports with typically developing children, the clinical population tested in this study demonstrated the presence of similar thresholds in the flat noise condition but thresholds were elevated in the notched noise masker condition. This pattern led to the reduced difference thresholds that suggest the auditory filter shape is at least in part, a contributing factor to the poor performance on this task. Further investigation will be required to determine the nature of the frequency resolution problems in this population of children. The determination of auditory filter size in children that present with elevated notched noise thresholds may be informative. Regardless of the cause for the poor frequency resolution performance observed in this study, the information obtained as a result of the study has been successful in identifying an area of potential difficulty that requires further investigation.

Chapter 6

6 Temporal Resolution as measured by gap detection thresholds

All sound occurs over time and important information is conveyed in the spectral changes that occur over the signal duration. Signal changes occur rapidly requiring the auditory system to perceive and process auditory information very quickly. An auditory system that is slow in processing acoustic changes in signals will provide blurry or inaccurate representations of the sound that can lead to confusion or misinterpretation of meaning at higher levels. This kind of temporal processing deficit is frequently suspected when an individual demonstrates normal hearing sensitivity but seems to respond to sound in ways that suggest hearing is not normal. The term temporal resolution is used to label abilities related to signal perception in time but the term can be quite vague as there are many ways to evaluate different aspects of temporal processing. Studies of temporal acuity have examined the perception of signal phase or time reversal (Green, 1973; Ronken, 1970), modulated signals (Bacon & Viemeister, 1985; Buunen & van Valkenburg, 1979), Huffman sequences (Green, 1973), and various masking paradigms (Hill, Hartley, Glasberg, Moore, & Moore, 2004; Viemeister & Plack, 1993). However, the most frequently used method for investigating temporal resolution is gap detection. During a gap detection task, the listener is asked to identify which of several signals has an embedded brief temporal gap. The signals are most often samples of noise that may be restricted in bandwidth.

6.1.1 Gap detection abilities in adults

The ability to detect a temporal gap in a signal has been extensively investigated in adults. In a series of four studies, Shailer and Moore (1983) investigated adult gap detection abilities. Signals were 400 ms in duration and centre frequency ranged from 400 to 8000 Hz. Three studies investigated the effects of signal parameters such as centre frequency, bandwidth, and spectrum level on gap detection thresholds. The fourth study investigated auditory filter shape through changes in the size of the spectral notch (gap) in the masker. They found that gap threshold remained fairly constant once the signal reached a spectrum level of 25 dB. The largest change in gap detection threshold as a function of signal spectrum level was observed for low frequencies. Gap detection threshold decreased (improved) with increasing frequency and poorer performance (elevated thresholds) was found with a narrow signal bandwidth. For a noise signal with a centre frequency of 1000 Hz and a bandwidth of 500 Hz, the average gap detection threshold for adult listeners was 8.1 ms. Fitzgibbons and Wightman (1982) investigated the effects of signal frequency and presentation level on gap detection thresholds in adults using three different octave-band noise signals and two levels. At both 30 and 85 dB SL presentation levels, the normal hearing adult listeners demonstrated a decrease in gap detection thresholds with an increase in signal frequency. Signal level also had a significant effect on the gap detection thresholds. Normal hearing listeners were able to detect smaller gaps when they were presented in more intense signals and the largest differences were noted for the lower frequencies. The average gap detection threshold decreased from an average of 9.46 ms for a 800-1600 Hz bandwidth to 5.09 ms for a 2000-4000 Hz bandwidth at an 85 dB SPL presentation level. At the 30 dB SPL presentation level the gap detection thresholds decreased from 12.38 to 6.06 ms for the same noise bandwidth signals respectively. Similar results for the effect of frequency on gap detection thresholds were obtained by Florentine, Buus and Geng (1999). They investigated temporal resolution in adults by estimating thresholds from psychometric functions for the detection of temporal gaps of varying duration. Signals used in their study included bandpass noise presented at 85 dB SPL at each of three centre frequencies, 500, 1000, or 4000 Hz. Results showed that gap detection thresholds decreased (improved) as centre frequency increased. Best performance (6 ms) was obtained at 4000 Hz. When the signal was a 1000 Hz bandpass noise, the average gap detection threshold was 12.7 ms. In order to obtain normative data for an auditory processing test battery, Shemesh (2008) evaluated the performance of adults on several different psychoacoustic tasks. He included two gap detection tasks in his test battery. Gap detection thresholds were obtained for a 500 ms white noise signal that contained a temporal gap at its centre and for two clicks for which the inter-stimulus-interval represented the temporal gap. Thresholds were lower and less variable for the task that employed the white noise signal as compared to the click signals. The average adult gap detection threshold for with the white noise was 3.97 ms

6.1.2 Gap detection abilities in typically developing children

Studies investigating the development of temporal resolution through the use of gap detection studies have shown that thresholds for infants are higher than those recorded in older children and adults. Werner, Marean, Halpin, Spetner and Gillenwater (1992) measured gap detection in children between 3 and 12 months of age and a group of adults. A series of conditions used a broadband noise presented at a 30 dB SPL spectrum level in a high pass masker noise to assess the effects of frequency on gap detection threshold. Three conditions were tested each with a different cutoff value for the high pass masker. Results showed that infants have elevated gap detection thresholds when compared to adults but began to approach adult levels by 12 months of age. Results also showed similar frequency effects in adults and infants with both age groups displaying decreasing threshold with increasing masker signal high pass cut-off frequency, i.e. with a broader bandwidth signal. The authors conclude that there is a significant improvement that occurs in the gap detection threshold during the very early years and that this likely relates to age- related changes in processing efficiency, temporal coding, and selective listening.

Gap detection threshold show age effects into the early school-aged period. Irwin, Ball, Kay, Stillman and Rosser (1985) investigated gap detection thresholds in children aged 6 to 12 years, and a group of adults. Both broadband and several narrowband noise signals were used. Presentation level of each octave band was 60 dB SPL for the 500, 1000, and 2000 Hz octave-band noises. The broadband noise was presented in a 40 and 60 dB SPL condition. Gap detection thresholds improved with increasing frequency for all age groups however the magnitude of improvement for the various age groups varied with frequency. The largest improvement in threshold with increasing age was seen at 500 Hz. The average gap thresholds recorded for 8 to 12 year old children ranged between 9 and 11 ms for 1000 Hz narrow band noise signals. Gap thresholds for the same age group ranged between 8 and 6 ms for the broadband signals. Temporal resolution via gap detection in young children aged 3 to 7 years was assessed by Wightman, Allen, Dolan, Kistler, and Jamieson (1989). Signals were 400 ms samples of half octave band Gaussian noise with a centre frequency at 400 or 2000 Hz. Signals were presented at 40 dB SPL spectrum level. A substantial amount of between and within subjects variability was found in the younger children. Thresholds for all ages were higher at 400 Hz than at 2000 Hz, consistent with previously reported frequency effects. Thresholds at both frequencies improved with increasing age. Average gap detection thresholds for the 3.5 to 5 year old children ranged from 14.5 to 9 ms. The 6.5 year old children performed similar to adults with average thresholds reported as 7 and 5.5 ms, respectively. Monte Carlo simulations suggested that the within subject variability and larger threshold values at younger ages may have been the result of both sensory and non-sensory factors such as attention.

6.1.3 Gap detection in clinical populations

The ability to segment words in speech is critical for the comprehension of what is heard. One cue used to segment words in speech includes a very brief silent period. Gap detection is one of the tests that can be used to assess the ability to detect this kind of brief temporal gap. Children with impaired language acquisition have been shown to have impaired temporal resolution and difficulty detecting the brief gaps in sound (Tallal, Merzenich, Miller, & Jenkins, 1998; Tallal, Miller, & Fitch, 1993; Walker, Brown, Scarff, Watson, Muir, & Phillips, 2011). Children with larger than expected gap detection thresholds may not necessarily demonstrate severe delays in language development but could experience difficulty detecting and recognizing temporal cues that are present in discourse due to difficulty segmenting words, especially if the speaker has a very fast rate of speech. The identification of brief silent periods in running speech is critical not only for the segmentation and recognition of words but also for the recognition of subtle suprasegmental cues. The interpretation of the linguistic content in speech can be carried in a subtle emphasis placed on the temporal gap between words (Cole & Jakimik, 1980). For example, whether there are two or three foods in the spoken list: “chocolate cake and strawberries”, is determined by the duration of the temporal gap between the first two words in the phrase. If the gap is slightly extended, then the chocolate and cake are two different foods but if the gap is almost non-existent then only one food item, chocolate-cake is present. Children with poor temporal resolution may be unaware of these suprasegmental cues and misunderstand what is said to them.

There is also evidence that some children with phonics and/or reading impairment have larger than expected gap detection thresholds (Hautus, Setchell, Waldie, & Kirk, 2003; Walker, Hall, Klein, & Phillips, 2006). The exact nature of the contribution temporal resolution makes to the development of phonics and reading is not clear but large gap detection thresholds are seen in children with reading impairment. Reading delay is frequently reported as a concern in the clinical population of children suspected of having an auditory processing deficit so it is not surprising that gap detection may be a problem for some of the children in this group. A study by Boets, Wouters, van Wieringen and Ghesquiere (2007) also found elevated gap detection thresholds in reading impaired children when compared to a control group of children but the group difference in thresholds was not significant. Therefore, there is a suggestion that the children with APD and those who have problems learning to read may have difficulty on tests of temporal resolution.

There are a several commercially available tests that tap gap detection function, attributable to the general belief that children with APD suffer from temporal processing deficits. These would include, for example, the Auditory Fusion Test – Revised (McCroskey & Keith, 1996), the Gap In Noise test (Musiek, Shinn, Jirsa, Bamiou, Baran, & Zaidan, 2005), and the Random Gap Detection Test (Keith, 2000b). These commercially available tests were designed with pre-recorded stimuli that contain a variety of gap sizes that are presented to the listener in a sequential or random order. The Adaptive Test of Temporal Resolution (Lister, Roberts, Shackelford, & Rogers, 2006) assesses gap detection with an adaptive signal presentation that approximates the flexibility of a psychophysical test method. This is achieved through a wav file bank of pre-recorded signals from which the computer selects the next presentation based on the previous listener response. Thresholds for children over the age range of 7 to 11 years obtained with commercially available gap detection tests range between 2 ms to 12 ms.

The differences across procedures may result from slightly different stimuli and procedures employed in the tasks (Chermak & Lee, 2005). Clinical measures of temporal resolution have achieved some level of popularity in clinical use (Emanuel, Ficca, & Korczak, 2011) but research involving the performance of pediatric clinical populations with this measure is limited.

6.1.4 Summary

Temporal resolution as assessed through a gap detection task has been extensively studied in normal adults and typically developing children. Results of these studies show that gap detection thresholds will vary with signal features. Thresholds will improve with increasing bandpass noise centre frequency and level (Fitzgibbons & Wightman, 1982), and a developmental trend has been observed in gap detection thresholds. Thresholds are higher for infants and young children with adult threshold levels achieved by approximately 6 years of age (Wightman et al., 1989). Children with language and/or reading impairments have been shown to have elevated gap detection thresholds (Tallal et al., 1998; Walker et al., 2011; Walker et al., 2006; Hautus et al., 2003). Although the extensive investigation of temporal resolution abilities as measured by the gap detection task has not been undertaken in children suspected of having an auditory processing disorder, there are several tests that have been developed and are being used for clinical assessment with this population (Emanuel et al., 2011).

The goal of this study was to use an adaptive gap detection task to investigate the temporal resolution abilities of children suspected of having an auditory processing deficit. It was hypothesized that some of the children considered part of the clinical population may have reduced temporal resolution. This theory was based on the acknowledgement that the accurate and efficient processing of signal temporal features is critical for the understanding of acoustic information. In the clinic, parents have been known to report that their child is better able to understand information if spoken slowly or that their child frequently misunderstands what they are told. Because children may have an improved understanding of speech that is presented at a reduced rate it is possible that temporal resolution is somewhat impaired in this group. A reduced rate of speech may accentuate gaps between words allowing children the time and signal clarity (achieved through the overt segmentation of words) they require to accurately process the information they hear. It was therefore postulated that some of the children suspected of having an auditory processing disorder may have impaired temporal resolution.

6.2 Method

This gap detection study in the clinical population adheres to the General Method as described in Chapter 2. This method section describes the study participants as well as the signal parameters and procedures that were unique to the gap detection study.

6.2.1 Participants

There were twelve children, 2 girls (8 – 9 years) and 10 boys (7 – 17 years) who participated in this study. All the children participated in the larger study investigating auditory processing abilities in children. The clinical classification of children into APD and non-APD groups resulted in 6 children falling into the non-APD group and 6 children obtaining a diagnosis of APD (based upon 2 or more of the 5 behavioral tests of central auditory function falling more than 2 standard deviations below expectations).

6.2.2 Signals & Procedure

Signals were three 400 ms samples of Gaussian noise, bandpass filtered with a centre frequency of 1000 Hz and a bandwidth of 400 Hz. On each trial, one sample had a silent interval centered in the noise and two did not. The gap was created using linear gating in order to obtain instantaneous onset and offset. To mask spectral splatter resulting from the insertion of the gap within the target stimuli, a continuous Gaussian notch-filtered masking noise with a centre frequency of 1000 Hz and a notch width of 400 Hz was presented at 25 dB Spectrum Level (58 dB SPL). All signals were passed through 10 ms cosine squared on/off gating ramps. Standard and target (gap) signals were presented at a constant intensity of 40 dB Spectrum Level (73 dB SPL). The 3 samples were separated by a 400 ms inter-stimulus interval. Signals were generated and presented as described in the general method. The initial gap size was 40 ms. Gap size was varied adaptively. Initially, the step size was 15 ms. Each reversal resulted in a change of the gap size by a factor of 0.5. The final step size for this task was 0.25 ms.

6.3 Results

All twelve children completed three 30 trial blocks. Thresholds were calculated for each block. Minimum requirements and threshold calculation was achieved as described in the general method. A one way within subjects repeated measures analysis of variance was conducted for the three blocks of trials. A statistically significant difference was not found between threshold estimates for the three blocks of trials, Pillai's Trace = 0.178, $F(2,10) = 1.082$, $p = 0.375$, $\eta^2 = 0.178$. Because there was no statistically significant difference between trial blocks, the three threshold estimates were averaged to produce a single discrimination threshold estimate. Figure 13 shows the average gap detection threshold for each listener plotted as a function of age and clinical group. Data for the APD and non-APD diagnosed children are shown by the open red square, and open blue diamond symbols respectively. Mean data from previous studies of typically developing children are shown by the filled red circle (Irwin et al., 1985), filled green triangle (Wightman et al., 1989), and filled blue square (Fitzgibbons & Wightman, 1982) symbols.

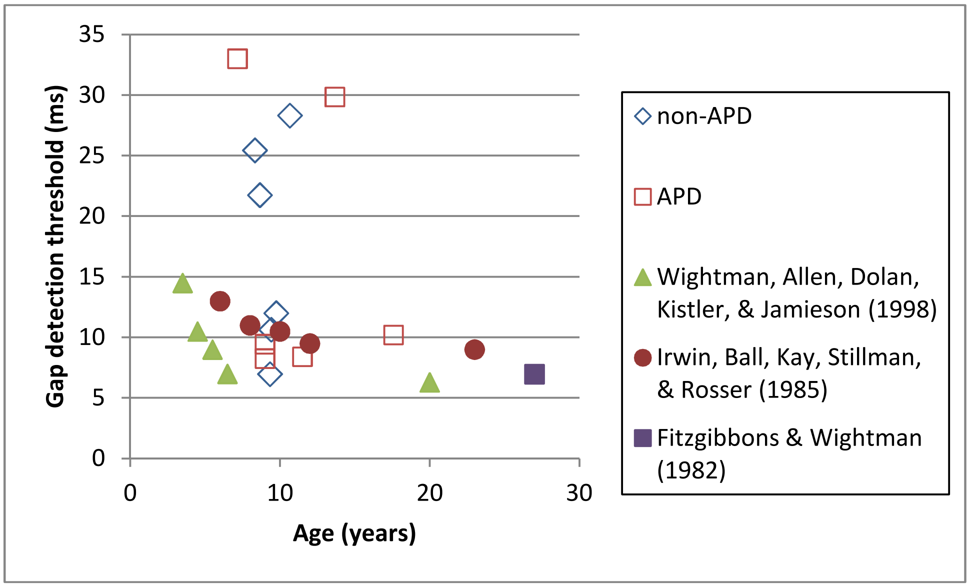


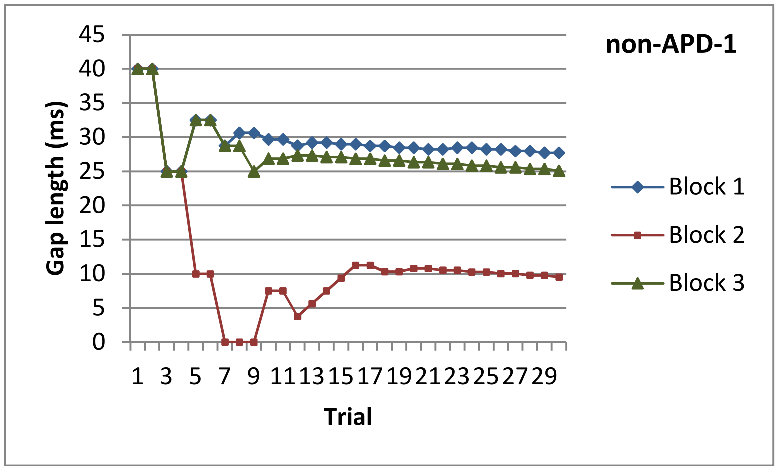
Figure 13 Gap detection thresholds are shown as a function of listener age and diagnostic group. Individual thresholds for the children classified as APD and those that are not are shown by the open squares and diamonds, respectively. Mean thresholds from typically developing children and young adults reported in the literature are shown by the filled symbols.

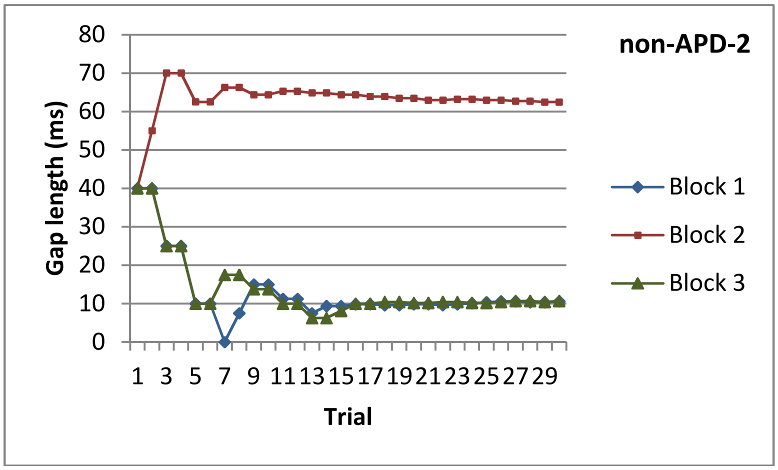
A substantial amount of variability was apparent in the data. Seven children, slightly more than half of the participants, achieved gap detection thresholds that were similar to typically developing children but there were children in both clinical groups that demonstrated elevated gap detection thresholds. Results of the study were evaluated using a one-way analysis of variance with the dependant variable gap detection threshold. The independent variable clinical group had two levels that included non-APD and APD. The average gap detection threshold achieved by the non-APD group was 17.5 ms with a standard deviation of 8.8 ms. The APD group of children achieved the average gap detection threshold of 16.5 ms with a standard deviation of ll.6 ms. The mean threshold and variance for the two groups appeared similar and the Levene statistic, the test for homogeneity of variances was not statistically significant $F(1,10) = 1.342$, $p = 0.274$ confirming the impression that the two groups performed in a similar fashion. The analysis of variance revealed that differences between the two groups were not statistically significant, $F(1,10) = 0.028$, $p = 0.871$, $\eta^2 = 0.003$. The two clinical groups performed in a similar fashion on the gap detection task.

6.4 Discussion

The purpose of this study was to investigate temporal resolution abilities in the clinical population of children with learning and academic problems, who were suspected of having an auditory processing deficit. This was accomplished through the evaluation of gap detection thresholds with a sample of 12 children from the clinical population, 6 of whom were identified as suffering from an APD based upon behavioral clinical tests and recommended clinical guidelines. The remaining 6 children, who were having difficulties as reported by their caregivers and teachers, were not classified as APD. The discrimination task involved the children listening to 3 samples of a narrowband noise, one of which contained a temporal gap (silent period) centred in the noise signal. Each child completed 3 blocks of 30 trials, each of which produced a threshold estimate. The 3 estimates were averaged when no repetition effect was found. Previous studies with typically developing children show adult-like gap detection thresholds by 6 years of age (Wightman et al., 1989) and as seen in Figure 13, seven children, slightly more than half of the participants in this study, achieved age expected thresholds. Five out of the twelve children that participated in this study displayed larger gap detection thresholds than expected for their age (Irwin et al., 1985; Wightman et al., 1989). Children with elevated gap detection thresholds were not exclusive to one diagnostic group. There was no significant difference between the gap detection thresholds achieved by the APD and non-APD groups. The temporal resolving abilities are not only similar between groups but difficulty with this task was not restricted to those listeners with the APD diagnosis as determined by a clinical battery of tests.

Of interest was the nature of the outlying performance by five of the twelve children that participated in the gap detection task. To further evaluate their poor performance, the trial-by-trial data for these five listeners was plotted and shown in Figures 14 and 15 for the non-APD and APD groups respectively. In both figures the listener responses (gap length in ms) are shown for each trial in all three blocks. In the adaptive forced choice procedure each incorrect response resulted in an increase in gap length. One correct choice resulted in no change in gap length. Two correct choices in a row resulted in a decrease in gap length. For all listeners, the three trial blocks are shown and identified for order of completion, Block 1 responses are represented by the blue diamonds, Block 2 responses are represented by the red squares, and Block 3 responses are represented by the green triangles. The response tracking for all listeners with outlying thresholds was similar in that the search narrows around threshold, the number of reversals is sufficient for threshold calculation and at least one block of trials achieves a typical classification for listening performance as described by Moore, Halliday, and Amitay (2009). The unexpected finding was that the listeners appeared to demonstrate a modification or change in their decision criterion or response bias (Ingram, 1970; Macmillan & Creelman, 1990; Swets, 1996, Chapter 11; Swets, Tanner, & Birdsall, 1988) for at least one block of trials. The decision criterion or response bias is a concept related to the listener's decisions regarding the presence or absence of the target, which in this study is the signal gap. Decision criterion involves the decision process used by the listener and their level of certainty that the target (gap) is present or that it is absent. If a line plot of gap size were drawn, the criteria would intersect the line between the points where the listener would consistently identify the target accurately and where they would report the absence of a target. If tracking around threshold remains consistent, but the decision criterion or response bias changes, then the threshold would shift with the criteria change. The result of one or more elevated block thresholds in the group of three blocks was an overall elevated average gap detection threshold. It is clear through inspection of the individual block trial-by-trial responses that all of the children with elevated thresholds were capable of achieving gap detection thresholds within the normal range. For some reason these five listeners demonstrated shifts in their response criterion between blocks of trials and this influenced the final threshold value. Without further study, one can only speculate about the reason for this change in decision criterion. In Figure 15, it could be postulated that the elevated threshold for listener APD-1 represented a learning curve because the elevated threshold occurred in the first block of trials and performance improved as experience was gained with the signals. This theory however would not apply to the other listeners with elevated thresholds because their elevated thresholds occurred in block two and/or three.





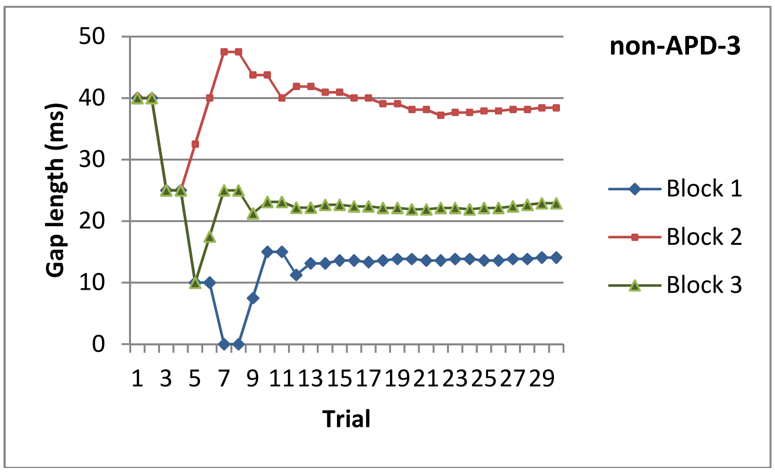
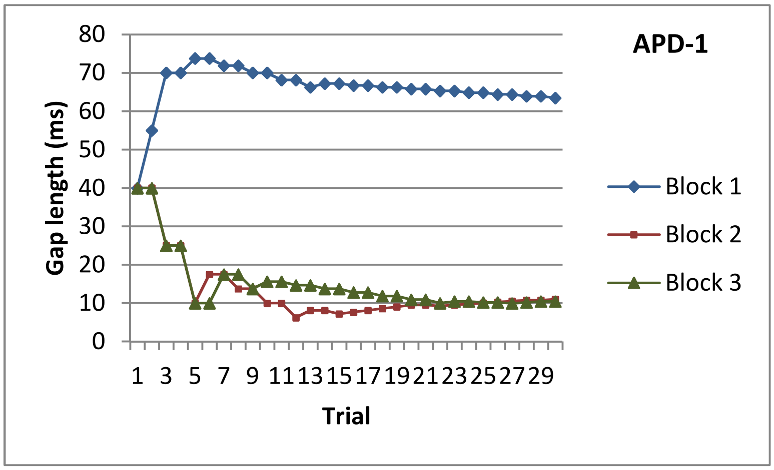


Figure 14 Responses are shown for three blocks of trials completed by three non-APD listeners that achieved an outlying average gap detection threshold. Responses are plotted as the gap length for each trial in the block. Trial Blocks 1, 2, and 3 are represented by the blue diamonds, red squares, and green triangles respectively.



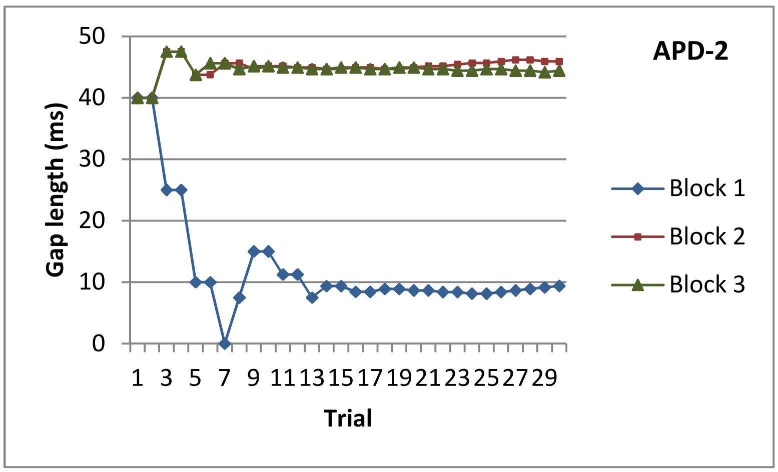


Figure 15 Responses are shown for three blocks of trials completed by two APD listeners that achieved an outlying average gap detection threshold. Responses are plotted as the gap length for each trial in the block. Trial Blocks 1, 2, and 3 are represented by the blue diamonds, red squares, and green triangles respectively.

The discovery of a change in decision criterion for a psychoacoustic task where success in threshold tracking has been demonstrated was an unexpected finding because this has not previously been reported or discussed in published studies. Implications include the need to consider the real-time presentation and classification of trial-by-trial responses when working with a clinical population and the inclusion of this type of feature in any device or software that may be developed for clinical application of psychoacoustic measures in the clinic. More importantly, the need to further investigate decision criterion and response bias in the clinical population is necessary to ascertain the cause or reason for this behaviour when it is displayed. It may be that this is a form of attentional APD as described by Moore et al. (2009) or there may be some other, higher-order cognitive function that contributes to this behaviour. Regardless of the root cause for the behaviour, it is important to determine if the change in decision criterion is a function of the test situation, state of the listener, or if the behaviour may be a reflection of qualitative changes in perception. Influences related to the test situation or the listener state at the time of testing can be identified and controlled. However, if the change in decision criterion is a result of perceptual changes it should be expected that these perceptual fluctuations would translate into daily experience and be displayed as fluctuations in performance. Because children identified as having auditory processing disorder have been described as having inconsistent classroom performance the possibility of fluctuations in perception cannot be completely discredited regardless of the unique nature of this finding.

There were 5 out of the 12 study participants that demonstrated elevated gap detection thresholds. Only 2 of the 5 participants demonstrating an elevated gap detection threshold had been identified as APD. This finding suggests that the clinical test battery used in the classification of children into the APD and non-APD groups was not sensitive to temporal resolution encoding abilities as measured by the gap detection task. Unfortunately, an interpretation of the study results is not straightforward. It was shown through the listener trial-by-trial performance that these elevated thresholds were not the result of consistent poor performance or the commonly observed inattentive performance, but the result of inconsistent performance resulting from a change in decision criterion for gap identification. Each of the listeners in this group of outlying performance actually demonstrated one or two trial blocks that achieved typical threshold search (Moore et al., 2009) and gap detection threshold. Further investigation of gap detection abilities and the influence of alterations in decision criterion must be conducted in order to determine the extent to which temporal resolution may be disordered in this or other clinical groups and to what extent these decision criterion shifts affect signal perception and translate into auditory behaviour.

Chapter 7

7 Temporal Integration

A number of early investigations into auditory sensitivity in adults revealed that short duration signals could not be detected without an increase in intensity (Green, Birdsall, & Tanner, 1957; Hughes, 1946; Plomp & Bouman, 1959; Stephens, 1973). It is often reported that this change in threshold with increased signal duration, known as temporal integration, is described by an 8 – 10 dB improvement in threshold for each decade increase in signal duration up to about 500 ms, or a change of 3 dB per doubling of duration for normal adult listeners. Beyond 500 ms no further change in threshold is reported (Garner & Miller, 1947; Olsen & Carhart, 1966; Watson & Gengel, 1969).

The improvement in detection threshold with increasing signal duration has been consistently reported for brief signals up to 500 ms but variations have been documented in the rate of threshold change due to factors such as signal type and research method. The signal selected for study will affect the rate of threshold change with signal duration (Garner, 1947a). Wide-band noise has a slower integration rate than pure tones which Garner (1947b) postulated were due to the increase in frequency bands requiring integration for the wide-band noise. Different rates of temporal integration were observed in adults as signal frequency changed (Pedersen & Elberling, 1972; Watson & Gengel, 1969). Steepest integration slope has been reported at 250 Hz with a decrease in integration rate with increasing signal frequency. The method of measuring temporal integration can make comparisons between studies difficult (Gerken, Bhat, & Hutchison-Clutter, 1990; Sheeley & Bilger, 1964). For example, in studies with adult listeners, Watson and Gengel (1969) (Gengel & Watson, 1971) compared temporal integration as estimated using the method of adjustment and a two alternative forced choice procedure. Smaller thresholds were obtained with the method of adjustment in comparison to those obtained with the two alternative forced choice procedure but a higher level of within-subject variability was observed in the method of adjustment data.

7.1 Models of Temporal Integration

Zwislocki, as early as 1960, suggested that temporal integration may take place in auditory nuclei of the central auditory nervous system. More specifically, he postulated that temporal integration takes place in the central auditory nervous system at a level beyond the first and second order neurons but before the crossed nerve tract junction. His theory is based on the combination of known neurophysiology, acoustics and experimental temporal integration threshold data. Zwislocki's (1960) calculations suggested that temporal integration does not take place in the cochlea because the activity observed in first order neurons is not consistent with what would be expected for longer duration signals if temporal integration was occurring in the cochlea. He also argued that the effective use of dichotic time differences for the purpose of sound source localization would necessitate temporal integration at or prior to the point where the nerve tracts from both ears cross.

Heil and Neubauer (2003) and Neubaur and Heil (2004) studied temporal integration functions in cats, using both continuous tones of varying durations and pulsed tone train stimuli of varying repetition rates. Data was collected with the cats prior to and then following the induction of cochlear impairment. They suggested that the apparent reduction in temporal integration functions following cochlear damage in the same animal was likely the result of the cochlear hearing loss, rather than a loss of temporal integration skills. Support for this theory was achieved by Heil and Neubauer (2003, 2004) through the development of a computational model. In their model, the shift in the threshold duration function observed in the hearing impaired cats can be shown to result from the change in hearing thresholds (baseline shift). The computational model can account for this hearing threshold shift and the result is threshold duration functions that are equivalent to those obtained when the animal had normal hearing thresholds. The demonstration by Heil and Neubauer (2003, 2004) that the appearance of a reduction in temporal integration in the presence of cochlear impairment is not actually a loss of temporal integration but only a shift in the temporal integration function that results from the threshold change (baseline shift) caused by the loss, is additional support for the theory that temporal integration occurs central to the cochlea (Zwislocki, 1960).

The role of the cochlear nucleus in temporal integration was studied in chinchilla by Clock, Salvi, Saunders and Powers (1993). This study involved the isolation of chopper and primary-like units in the cochlear nucleus in 8 adult animals. Centre frequency was identified for each unit and thresholds were recorded for a series of tone burst durations. The measured threshold-duration functions were similar to psychophysical data in humans and suggest that temporal integration is represented in the cochlear nucleus. The threshold-duration functions revealed that the nerve fiber thresholds improved for durations from 8 ms up to 512 ms. Preliminary data was also collected from 11 auditory nerve fibers in one animal. Integration functions from the auditory nerve did not demonstrate a resemblance to the psychophysical temporal integration data suggesting that temporal integration takes place central to the cochlea and most likely in the lower brainstem.

As a continuation in their study of temporal integration and a supplement to the study of the cochlear nucleus, Clock-Eddins, Salvi, Wang, and Powers (1998) investigated temporal integration in the auditory nerve fibers of chinchilla. Threshold-duration functions were recorded from auditory nerve fibers in 6 adult animals. Improved thresholds with an increase of duration were observed in approximately 60% of the auditory nerve fibers. The threshold duration functions for these fibers displayed slopes that were similar to those obtained from the cochlear nucleus up to approximately 256 ms. Based on these observations the authors suggested that temporal integration is initiated in the auditory nerve but that further processing must take place at higher centres in the auditory nervous system to achieve behavioural threshold duration function levels.

Using the data generated from studies that have been conducted to investigate the change in detection threshold for brief duration signals, models of temporal integration have been generated. These models attempt to describe the observed phenomenon and fall into two major camps. The power or energy integration model has been reported in a number of different equation forms but all are seated in the belief that the energy or power of the signal is accrued over time. Variations of the energy integration model were reviewed and tested by Gerken, Gunnarson, and Allen (1983). The authors fit the power-function and exponential models to threshold - duration data and propose that the best model to fit the data is a combination of the two equations and report reasonably good fits with the combined model. An alternative to the energy integration model was proposed by Viemeister and Wakefield (1991) who argued that the long course of auditory temporal integration was inconsistent with some of the postulated energy integration models. They proposed that the long-term temporal integration of a signal may occur through the accumulation of an increasing number of brief samples or looks at the signal rather than a long-term integration of the signal power. The model proposed by Viemeister and Wakefield (1991) involved processing that was similar to what has been described for temporal resolution including a critical band filter and a short time constant window. The short time constant for temporal integration would be on the order of the constant observed in temporal resolution. The short term memory for these acoustic signal samples or looks would have its own time constant so that the accumulated information can be analyzed or undergo computations. For example, an increase in the duration of a tone would increase the number of samples/looks that would accrue over the observation interval and these would compute into a change in threshold. The benefit of such a model is that it is able to account for both temporal resolution and temporal integration performance as described in the published literature.

To test their model Viemeister and Wakefield (1991) conducted two experiments with adults using a series of signals that incorporated systematic changes in the duration of the inter-stimulus interval between two signals. This was a significant deviation from the types of signals typically utilized in studies of temporal integration when thresholds are recorded for a series of signals that systematically change in their overall duration or in the number of brief tone iterations. In their first study, psychometric functions were obtained for the detection of a single pulse and pulse pairs of various inter-pulse intervals. Test results revealed a 4 dB improvement in thresholds for tone pairs with a separation between 1-5 milliseconds. This improvement in threshold is greater than what would be expected based on power integration models. For separations between tone pairs that are greater than 5 ms there was a smaller improvement in threshold, approximately 1.6 dB. This is consistent with predictions if the looks were independent. Viemeister and Wakefield (1991) contend that this data fits the multiple looks model because when the separation between tone bursts is smaller than the time window, thresholds change as expected from power integration models but at larger separation values thresholds change as expected for integration that occurs for independent looks at the signal.

The second experiment conducted by Viemeister and Wakefield (1991) further evaluated the multiple looks model by obtaining thresholds for tone pairs that were separated by an inter-stimulus interval occupied by a noise. In this signal, the tone level and inter-stimulus duration were held constant and the intervening noise level was systematically changed. If the model held, then the looks for the signal would be independent and not affected by the intervening noise signal. As predicted, the thresholds for two tones improved by slightly more than expected and then remained essentially unchanged regardless of the changes in noise stimuli.

The experiments conducted by Viemeister and Wakefield (1991) supported the multiple looks model but there remained the question of whether the model could account for long duration steady state signals that follow energy detection. They suggested that for long duration signals, the signal looks would all contain the same energy and, when summed, would produce threshold shifts equivalent to energy detection. This hypothesis was tested by applying the multiple looks model, using a 3 msec time window, to the continuous tone data obtained by Plomp and Bouman (1959). Except for those signals that continued beyond 400 msec the multiple looks model accurately reflected the data obtained in the 1959 study by Plomp and Bouman (1959). Deviations of the model at the relatively long signal durations were postulated by Viemeister and Wakefield (1991) to be due to memory limitations.

Through four experiments using 8 different tone frequencies, 8 different inter-stimulus durations and 3 different number of tone bursts per stimulus presentation, Hoglund and

Feth (2009) investigated both temporal and spectral integration. The experiments systematically assessed temporal integration, spectral integration, and then the combination of temporal-spectral integration in adult listeners. When assessed as a single dimension, temporal integration results supported the multiple looks hypothesis. No difference in threshold was observed for different inter-stimulus interval spacing and threshold improvement with the doubling of presentations agreed with changes seen in the Viemeister and Wakefield (1991) study. There was no significant effect of tone frequency on the temporal integration thresholds. Threshold improvements for spectral integration were smaller than those observed for temporal integration. Hoglund and Feth (2009) suggested that a multiple looks model may not apply to the spectral domain or that the processing does not occur in the same way as it does for temporal integration. Regardless of the spectral integration model at work, when both spectral and temporal information is being integrated the amount of integration that could occur appeared to be limited by the spectral integration function.

7.2 Temporal integration in typically developing children

In normal hearing adults, temporal integration values can range from 6 to 10 dB for every ten-fold increase in duration. There are few temporal integration studies that have included children. Normal hearing children (6 to 14 years) obtained similar thresholds across the frequency range tested (500 and 4000 Hz) in a study conducted by Barry and Larson (1974). They employed the method of limits to obtain thresholds for pure tone signals at durations of 20 and 500 ms. Improvement in detection thresholds were approximately10 dB. In another study, Olsen and Buckles (1979) obtained measurements with normal hearing individuals ranging in age from 6 to 24 years. Signals included brief 1000 and 4000 Hz pure tones with durations of 10 and 500 ms. Thresholds were averaged across frequency at each duration. Thresholds for the 10 ms signals were referenced to the 500 ms signal threshold so the average improvement in threshold for all ages had a range of 6 to 8 dB meaning that the 10 ms signal threshold was 6 to 8 dB higher (elevated) in comparison to the 500 ms threshold. Olsen and Buckles (1979) reported that the 6-7 year age group displayed the shallowest slope in the temporal integration function but that there was no systematic change in thresholds with signal duration as a function of age. A significant developmental trend in the improvement in threshold with increased signal duration was noted for the children participating in a study conducted several years later by Maxon and Hochberg (1982). Thresholds for temporal integration were combined across frequency because the trend in threshold improvement with increased signal duration did not vary significantly by frequency but it does make direct comparisons with other single frequency studies difficult. They observed an average temporal integration improvement of 20.8 dB in thresholds obtained across four frequencies for durations that ranged between 25 – 800 ms in children 4 – 12 years of age. Thresholds were poorest (elevated) for the shortest duration signals with threshold improvement (decrease) observed as signal duration increased. To investigate temporal processing abilities in children and adults, He, Buss, and Hall (2010) used temporal integration and temporal selective listening tasks. The temporal integration task used 6500 and 1625Hz signals that were presented in a continuous Gaussian noise. Children ranging in age from 4.9 to 10 years and a group of adults completed the three alternative forced choice task to obtain thresholds for both signals at four durations. A decrease (improvement) in threshold was noted with the increase in signal duration. Children under 7 years of age had thresholds that were elevated in comparison to the older children and adults but similar threshold-duration functions were evident. Thresholds were found to decrease by approximately 3dB for the doubling of duration up to 32 ms and then the change in threshold reduced. An interaction of age, duration and frequency was noted and specifically relates to the performance of the under 7 years age group. Most recently, Moore, Cowan, Riley, Edmondson-Jones, and Ferguson (2011) conducted a study of auditory processing abilities in 6-11 year old children. Thresholds were obtained for a 1000 Hz tone at 20 and 200 ms durations. They found the highest thresholds and greatest performance variability for both signal durations in the youngest (6-7 years) age group. An improvement (decrease) in thresholds was seen with age across all age groups for both signal durations. The difference in thresholds for the two signal durations was considered the temporal integration threshold. Median temporal integration thresholds for the average age groups 6.5, 8.5, 10.5 and adults were reported as 16, 10, 8.5, and 7 ms respectively.

7.3 Temporal integration in the clinical population

The inability to process brief and fleeting sound has for some time been suspected as a contributing factor toward auditory, reading, and/or speech-language disorders in children. Difficulty identifying brief gaps in signals or processing signals that are separated by brief inter-stimulus intervals has been demonstrated in some children with speech, reading or auditory disorders suggesting that they may indeed have difficulty processing temporal features of signals (Heiervang, Stevenson & Hugdahl, 2002; McCroskey & Kidder, 1980; Tallal, Merzenich, Miller, & Jenkins, 1998;Tallal & Piercy, 1973). To date however, there are no studies investigating the ability of these children to process brief duration signals such as those used in a temporal integration study.

A number of recent investigations into the processing of auditory signals in children with and without phonological, speech or auditory disorders have involved physiological tests including the acoustic reflex and auditory evoked potentials. Several auditory electrophysiologic studies have focused on auditory brainstem responses evoked with click and/or speech signals. Results have shown that at least some of the study group children do not have normal responses. Children with phonological disorders have displayed delayed brainstem wave latencies for both click and speech signals (Goncalves, Wertzner, Samelli, & Matas, 2011). Degraded waveform morphology has been seen for the speech evoked auditory brainstem response in children with language-learning problems (Wible, Nicol, & Kraus, 2004). Children with specific language impairment have shown longer absolute wave latencies and atypical waveform morphology in auditory brainstem responses elicited to click stimuli (Basu, Krishnan, & Weber-Fox, 2010). The auditory brainstem responses in children suspected of having or confirmed with auditory processing disorder have shown atypical latency and morphology (Allen & Allan, 2007; Gopal, Daily, & Kao, 2002; Gopal & Kowalski, 1999; Jirsa, 2001; Purdy, Kelly, & Davies, 2002). Children with confirmed speech-in-noise difficulties have shown atypical speech evoked auditory brainstem response morphology (Anderson, Skoe, Chandrasekaran, Zecker, & Kraus, 2010; Hornickel, Chandrasekaran, Zecker, & Kraus, 2011). Additional evidence in support of atypical auditory processing at the brainstem level in some children with auditory disorders, there have been studies that demonstrate elevated and/or absent acoustic reflexes in this population (Allen & Allan, 2007; Attoni & Mota, 2010; Attoni, Quintas & Mota, 2010).

The evidence from these studies investigating early physiologic function in the auditory nervous system reveals the presence of atypical results in children with auditory disorders. Models developed through the analysis of behavioural thresholds and animal research suggest that temporal integration occurs early in the processing of auditory signals and has been completed at the level of the brainstem (Zwislocki, 1960; Clock-Eddins, Salvi, Wang, & Powers, 1998). These studies in combination with those suggesting that the encoding of temporal features may be a problem for children suspected of having an auditory processing disorder are sufficient evidence to suggest that children suspected of having an auditory processing disorder may have difficulty processing very brief signals which in turn would lead to atypical temporal integration threshold-duration functions. Knowing if temporal integration is impaired in the clinical population could be helpful in determining if signal encoding problems might be a contributing factor to their listening difficulties and if some of the more peripheral structures of the central auditory nervous system may be affected. Given what appears to be a high level of specificity in the site of temporal integration coding, behavioural measures of temporal integration could have the potential to be extremely useful as a diagnostic tool in the investigation of auditory disorders.

7.4 Purpose of the study

The purpose of this study was to investigate temporal integration in children with suspected auditory processing disorder using a series of pure tones that differed in duration. Unlike the other signal encoding abilities assessed in this project, the number of previous studies completed in this area is sparse and normal performance for comparison purposes with the clinical population was not readily available. For this reason it was deemed necessary to include comparison groups in the study.

7.5 Method

7.5.1 Ethics Approval

Approval of this project was secured from the University of Western Ontario, Office of Research Ethics (Appendix C). Parents were required to read the study Letter of Information and sign a consent form for study participation prior to the child's enrollment in the study (Appendix D). Verbal assent was obtained from each child at the beginning of the study and continued to be obtained from the participant on an ongoing basis in advance of each measure or activity during the test sessions. There was no penalty for withdrawal from the study. Adult participants were required to read the study Letter of Information and sign a consent form for study participation prior to their enrollment in the study (Appendix D). Adult participants were not paid for their involvement in the study.

7.5.2 Participants

Adults were recruited from research associates and students in the Child Hearing Research Laboratory and the School of Communication Sciences and Disorders at the University of Western Ontario. School-aged children were recruited from London, Ontario and the surrounding area by way of a letter of information that invited typically developing children and children with or suspected as having an auditory processing disorder. To be enrolled in the study, all participants were required to demonstrate normal pure tone thresholds and middle ear function (ASHA, 1994). If a child was excluded from the study due to hearing loss and/or middle ear dysfunction, their parents were informed of their child's hearing assessment results and they were referred to the appropriate community professionals for follow-up. A total of 21 listeners, 7 adults and 14 children, were recruited for the study. The group of 7 adults included 5 females and 2 males. The group of 14 children included 5 typically developing children (defined as experiencing no academic difficulties at school, no reports of listening problems in the classroom or other noisy environments, the absence of any behaviour that would suggest listening skill deficits, and no parental concern regarding academic and general developmental progress), 4 males and 1 female, ranging in age from 9 to 14 years.

Children with or suspected of having an APD included 9 children, 6 males and 3 females, ranging in age from 7 to 14 years. Their diagnosis was confirmed according to clinical protocols recommended by Chermak and Musiek (1997) and more recently in the American Academy of Audiology Clinical Practice Guidelines (2010). Allocation into the APD group was made if a listener failed one auditory processing test by greater than three standard deviations below the age mean or failed both tests by greater than two standard deviations below age mean. Two commercially available auditory processing tests, the Staggered Spondaic Word Test (SSW) (Katz, 1998) and the Pitch Pattern Sequence Test (PPS) (Pinheiro, 1977), were administered and scored according to their instruction manuals. The test order was balanced so that half of the children completed the SSW first and the other half completed the PPS first.

7.5.3 Procedure and test signals

All testing was completed at The University of Western Ontario Child Hearing Research Laboratory. Participants attended at least one full day test session which allowed for sufficient time to complete the testing. Adults completed all the measures in one day. Children frequently chose to attend more than one day of testing to complete all the required measurements. Periodically, participants were offered rest breaks and refreshments. At the completion of testing each child participant was given their choice of a small toy or school supply as thanks for their participation in the study.

Absolute thresholds were obtained for a series of continuous tones using a psychoacoustic task. Signal test order was randomized. Absolute thresholds were measured using an adaptive two interval, three alternative forced choice paradigm with feedback. The forced choice paradigm employed in this study was presented in a video game format similar to the one developed by Wightman, Allen, Dolan, Kistler, and Jamieson (1989) as described in the General Method, Chapter 2. Temporal integration functions were obtained by having every listener complete three blocks each (30 trials in every block) of the 6 test conditions for a total of 18 blocks (540 trials) in all. A block of trials was considered complete when a minimum criterion of 4 reversal points was achieved for threshold calculation. Each block took approximately 7 minutes to complete resulting in approximately 2.1 hours of testing. Prior to initiating data collection, listeners completed one practice block of ten trials (included a selection of the test stimuli) to ensure that instructions had been understood and that the starting levels were appropriate. Extensive training was not necessary for the listeners. Completion of all conditions in one test session was preferred but testing for some child participants was segmented and conducted across two days, for reasons of listener comfort or family convenience. In the cases where more than one test session was required, all testing was completed within one week.

Detection thresholds were measured for tonal signals of varying duration. The series of six signals were designed so that duration systematically increased through the doubling of the tone plateau. The stimuli were similar to those described by Neubauer and Heil (2004) and are depicted in Figure 16. Thresholds were obtained for single brief 6.25 kHz tones that have a rise and fall time of 4.16ms and the initial signal had no plateau (only the 4.16 rise and fall time)., The durations of the steady state signals were 8.32, 16.64, 41.6, 74.88, 141.44, and 274.56 ms. Each of the steady state signals had gated cosine-squared onsets and offsets. All stimuli were presented in quiet. Detection thresholds were measured for each of the stimulus durations.

A Dell Dimension 8100 desktop computer with the Tucker Davis Technologies (TDT) System 3 RP2 realtime signal processor digitally generated the tonal stimuli and controlled the adaptive presentation procedure. The Dell computer and TDT System were located outside the Eckoustic Noise Control room (sound room) to reduce the amount of listener exposure to equipment noise during the test session. The signals were digitally generated with a 50 kHz sampling rate and processed through a 24 bit Sigma Delta digital-to-analog converter. The signal output from the TDT HB7 headphone driver was connected, through the patch panel, to an Etymotic Research ER-2 transducer earphone located in the sound room where the listener received the test signals. Level calibration was conducted acoustically through the experimental set-up prior to the initiation of the study and then routinely throughout the duration of the study. Calibration was completed with a Bruel and Kjaer measuring amplifier (Type 2610) and associated preamplifier (Type 2639 with Adaptor DB1021), microphone (Type 4144), and artificial ear (Type 4152). Noise floor measurements were conducted with a Bruel and Kjaer Hand Held Analyzer (Type 2250) and associated preamplifier (Type 2669) and coupler system (Bruel and Kjaer 4157 Ear Simulator with integrated Type 4131 microphone).

Starting level of the target stimulus varied with each condition such that the stimulus began at a comfortable and easily detected level. To obtain an absolute threshold for the target stimulus, the standard or comparison stimulus presentation level was set at 0 dB SPL and the duration was set at 0 ms so that no sound, other than the target stimulus, could be heard during a trial. A two-down, one-up adaptive procedure as described by Levitt (1971), tracking the 70.7% correct response level, was employed in the 3AFC task. With this adaptive procedure the tone level is reduced after two consecutive correct responses, remains unchanged after only one correct response or is increased following an incorrect response. To quickly and efficiently achieve threshold bracketing, initial target signal step size was 15 dB SPL to the first reversal (change of tracking direction) after which the stepsize was reduced by half until it reached a minimum of 2 dB where it remained for the remainder of that block. Threshold was calculated as the average of the midpoints between the reversal points in a block of trials. Absolute thresholds for each block were calculated on an ongoing basis, during listener breaks in the session, to ensure both participant vigilance and success in meeting the criteria of 4 reversal points in each block of trials. Three threshold estimates were obtained for each signal condition and subsequently averaged. The thresholds across signal conditions were used to obtain a temporal integration function.

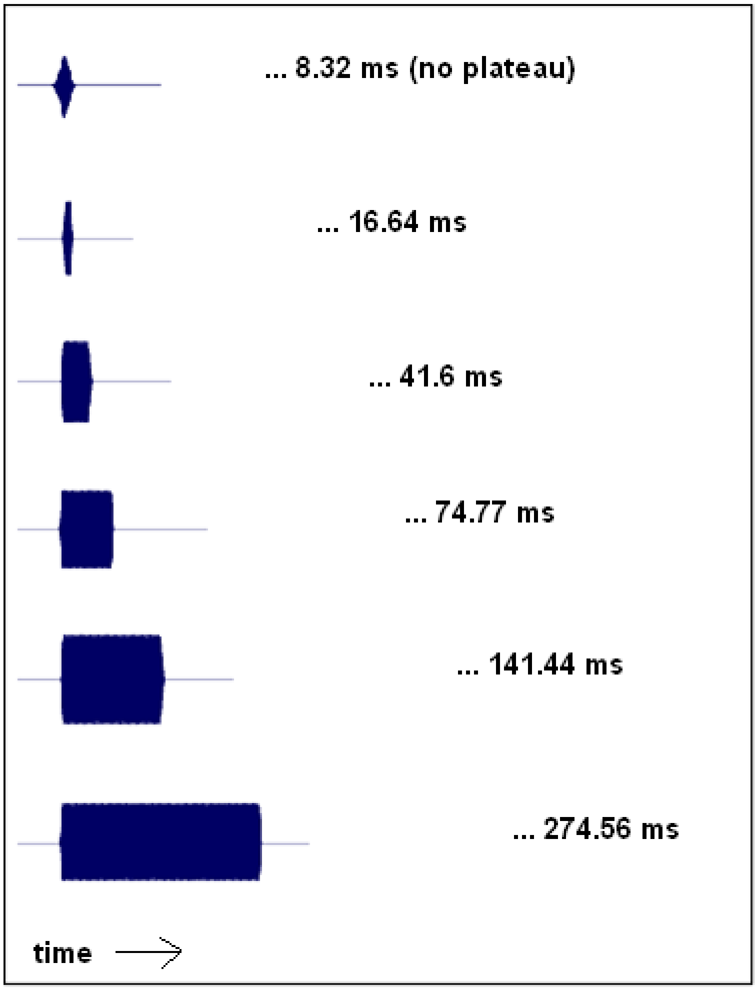


Figure 16. Graphic representation of the 6 tone stimuli used as the signal series in the temporal integration study. Each signal is a 6.25 kHz tone. The first signal shown at the top of the figure and in a different scale to the other signals, had no plateau and total duration of 8.32 ms that was obtained from the rise and fall time of 4.16ms. The subsequent 5 tone stimuli graphics represent the increasing signal duration obtained from a doubling of the signal plateau. The initial increase in signal duration (signal 2^{nd} from the top) was achieved by the inclusion of an 8.32 ms duration plateau inserted between the same 4.16 ms duration rise and fall times that composed the first signal. An increase in signal duration was achieved in subsequent signals through the lengthening of signal plateau.

7.6 Results

Each listener completed three blocks of trials for each signal condition for a total eighteen blocks of trials. A repeated measures analysis of variance was conducted to ascertain whether differences existed between the absolute thresholds obtained on three blocks of trials in each signal condition for every listener. The results of these analyzes are presented in Table 1. There were no statistically significant differences between the thresholds obtained in the three blocks of trials for any of the six signal conditions. The three block thresholds for each signal condition were therefore averaged to obtain a single threshold for that signal for every listener. Subsequent analyzes were conducted with the average threshold value.

Absolute thresholds were achieved for six signals for each listener. Figures 17, 18, and 19 show the series of six tone thresholds as a function of duration for each individual listener in the adult, typically developing children, and APD groups respectively. For each figure the individual listeners are represented by a unique symbol and colour.

Table 1. Test results for the repeated measures analysis of variance between the thresholds obtained for three blocks of trials for each of the six signal conditions. Results show that the thresholds did not vary significantly and could therefore be averaged into a single threshold value for each of the signal conditions.

Repeated Measures Analysis of Variance				
Signal	***F***	**df1**	**df2**	**Significance value**
8.32 ms	0.258	2	17	0.775
16.64 ms	0.962	2	17	0.402
41.6 ms	1.224	2	17	0.319
74.56 ms	1.725	2	17	0.208
141.12 ms	0.292	2	17	0.750
274.56 ms	1.144	2	17	0.119

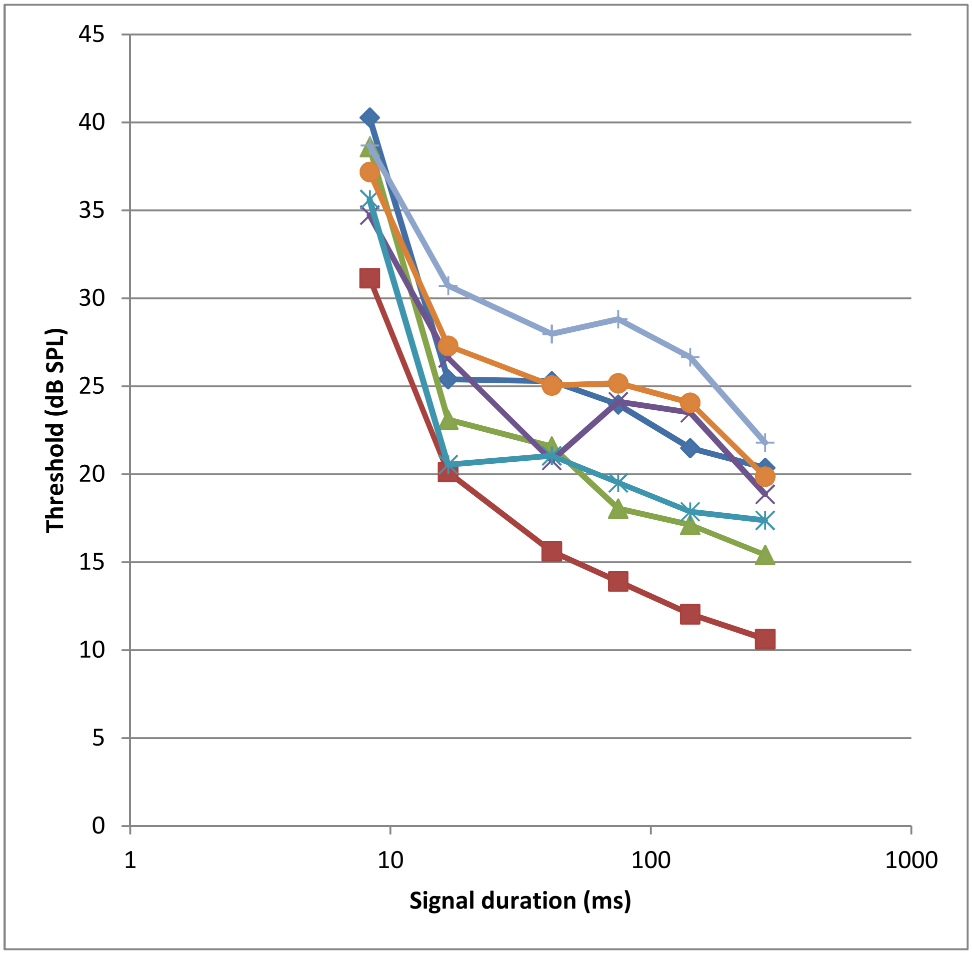


Figure 17. Absolute detection thresholds achieved by the adult group for 6.25 kHz pure tones are plotted on a logarithmic scale according to signal duration. Each individual listener is identified with a unique colour and symbol.

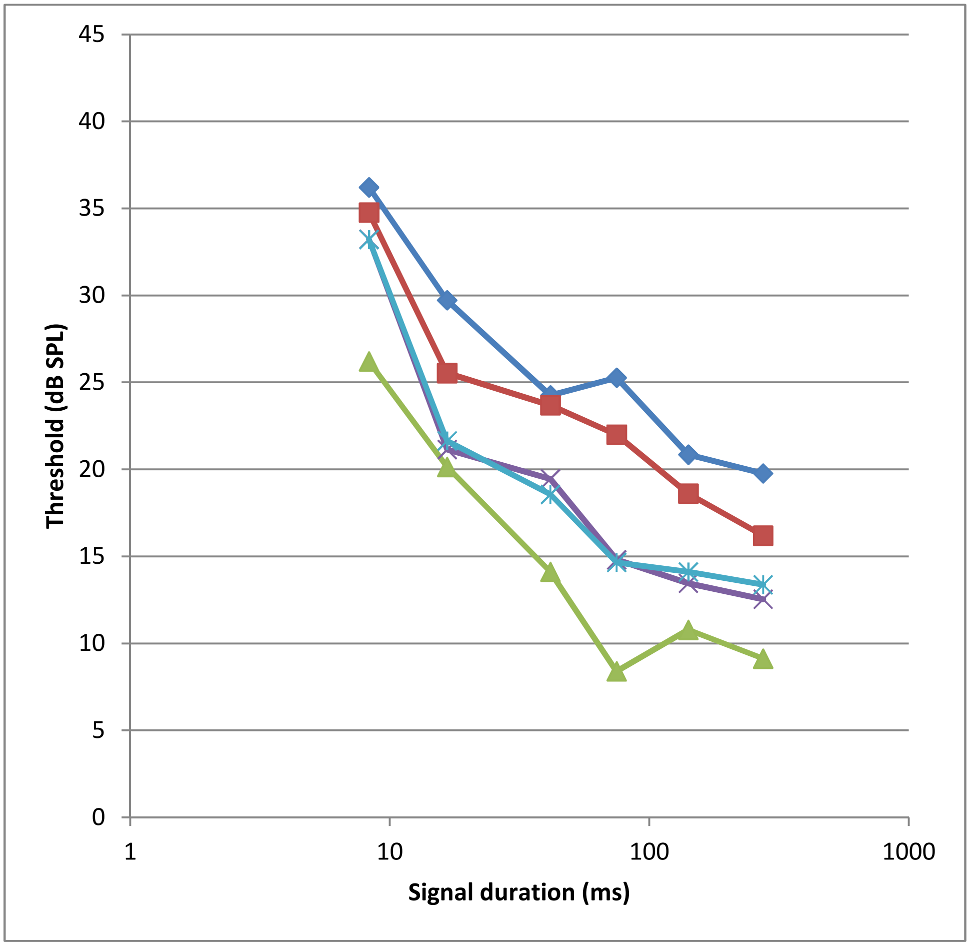


Figure 18. Absolute detection thresholds obtained by the typically developing children for 6.25 kHz pure tones are plotted on a logarithmic scale according to signal duration. Each individual listener is identified with a unique colour and symbol.

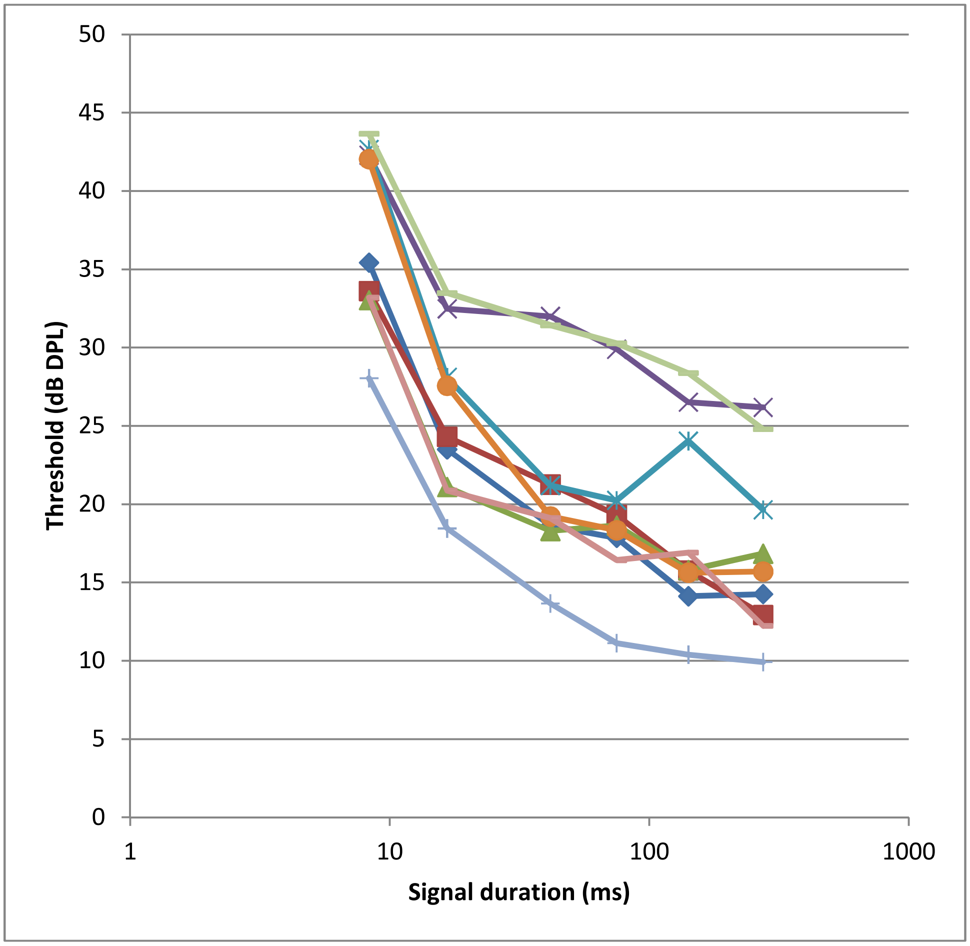


Figure 19. Absolute detection thresholds obtained by the children identified with auditory processing disorder for 6.25 kHz pure tones are plotted on a logarithmic scale according to signal duration. Each individual listener is identified with a unique colour and symbol.

Substantial individual differences were seen within each group. Some outliers appeared to be present in the APD group suggesting that the variability may be greater in this group. Levene's test of equality of error variances, obtained through a multivariate analysis of variance, and shown in Table 2, revealed similar variance in the thresholds obtained across the listener groups for each signal condition. Results of the univariate analysis of variance for each signal, shown in Table 3, revealed no statistically significant difference in the thresholds achieved by the three listener groups in each of the signal conditions. The improvement in absolute threshold with increasing tone duration was statistically significant, Pillai's Trace = 0.985, $F(5,14) = 185.251$, $p = <0.001$, $\eta^2 = 0.985$. The total average (standard deviation) improvement in absolute threshold with increasing duration was 18.85 (2.5), 18.53 (1.8), and 20.16 (3.3) ms for the adult, normal, and APD groups respectively. Variance in performance, as measured by Levene's test of equality of error variances, was not found to be significantly different between the groups, $F(2,18) = 0.876$, $p = 0.433$. A statistically significant difference was not present between the three groups for the magnitude change in threshold over the course of the signal series, $F(2,18) = 0.728$, $p = 0.496$, $\eta^2 = 0.075$.

Table 2. Test results for homogeneity of variance are shown for each of the six steady state signal conditions. Levene's Test results are shown for each signal duration.

Levene's Test of Equality of Error Variances				
Signal	***F***	**df1**	**df2**	**Significance value**
8.32 ms	2.734	2	18	0.092
16.64 ms	0.705	2	18	0.507
41.6 ms	0.448	2	18	0.646
74.56 ms	0.172	2	18	0.844
141.12 ms	0.787	2	18	0.470
274.56 ms	0.736	2	18	0.493

Table 3. Results from the univariate analysis of variance, evaluating threshold differences across groups, are shown for each of the six signal duration conditions.

Univariate ANOVA Test Results					
Signal	***F***	**df1**	**df2**	**Significance value**	Partial Eta Squared
8.32 ms	1.520	2	18	0.245	0.144
16.64 ms	0.180	2	18	0.837	0.020
41.6 ms	0.330	2	18	0.723	0.035
74.56 ms	0.967	2	18	0.399	0.097
141.12 ms	1.148	2	18	0.339	0.113
274.56 ms	0.884	2	18	0.446	0.086

A function was fit to the data for each individual using XLfit Version 5.1.1 (IDBS, 2009). The best fit to the steady state tone data for all six signal thresholds was a two phase exponential decay function. This resulted from the initial rapid improvement in threshold followed by a slower rate of threshold change. The two phase exponential decay function best fit was achieved with the form ((E+(A*exp((-1*B)x)))+(C*exp((-1*D)x))) where the steep portion of the decay function is controlled by (C*exp((-1*D)x)) and the slower rate of decay is controlled by (A*exp((-1*B)x)). In this function, E represents the lower asymptote, B & D are decay constants and A & C represent the maximum value of y. Previous studies of temporal integration have not required the use of a two phase function to fit threshold data. The steep portion of the two phase function was necessitated by the inclusion of the 8 ms signal in the series of signal durations. Signals of such brief duration were not typically employed in past studies so it was hypothesized that the initial rapid decay was linked to the brief 8 ms signal thresholds. It was evident that if the 8 ms threshold was removed from the signal dataset the best fitting function would no longer require two phases and would be more similar to functions previously reported in the literature. To determine if there were any differences between the functions that were fit to the data for the three groups, a univariate analysis of variance was conducted for each of the variables in the two phase exponential decay function. Results of Levene's test of equality of error variances are displayed in Table 4 and demonstrate that variance between groups for each of the equation variables is not equivalent for all but one variable (B). The analysis of variance conducted for each equation variable is displayed in Table 5 and demonstrate that there were no statistically significant differences between groups for any of the equation variables.

Table 4. Test results for homogeneity of variance across groups are shown for each of the five function variables that are fit to the threshold data. Levene's Test results are shown as a function of the each equation variable.

Levene's Test of Equality of Error Variances				
Signal	**F**	**df1**	**df2**	**Significance value**
Variable A	31.119	2	18	<0.001
Variable B	3.395	2	18	0.056
Variable C	12.190	2	18	<0.001
Variable D	12.190	2	18	<0.001
Variable E	30.247	2	18	<0.001

Table 5. Results from the univariate analysis of variance evaluating differences between groups for each of the five equation variables in the functions that were fit to the threshold data.

Univariate ANOVA Test Results					
Signal	**F**	**df1**	**df2**	**Significance value**	Partial Eta Squared
Variable A	2.691	2	18	0.095	0.230
Variable B	1.305	2	18	0.296	0.127
Variable C	1.714	2	18	0.208	0.160
Variable D	1.714	2	18	0.208	0.160
Variable E	2.912	2	18	0.080	0.244

7.7 Discussion

The three groups included in this study performed in a statistically similar fashion for the signals used to obtain temporal integration functions. This result suggests that, as a group, children with auditory processing disorder do not perform differently in comparison to typically developing children and adults but it is evident through a visual inspection of Figure 19 that there were at least two children in the APD group that performed differently than the rest of their group. These two APD listeners demonstrated thresholds that were elevated in comparison to the rest of their group. Two additional children in the APD group demonstrated elevated thresholds for only the 8.32 ms signal. Although the analysis of the group thresholds suggest the absence of a statistical difference, the individual performance suggests that a minority of children may be experiencing difficulty encoding brief signals and for a very few, the difficulty encoding temporal information may be even more difficult. The inability of the statistical analysis to identify these differences does not mean that the observed pattern of responses is inconsequential. Indeed, the elevation of these thresholds may be clinically significant. For this reason, temporal integration was investigated using the three alternative forced choice method in the clinical population described in Chapter 2. Signal frequency and the number of duration conditions were reduced in order to more closely approximate a clinically useful brief tone audiometry paradigm.

7.7.1 Brief tone audiometry in children suspected of having an auditory processing disorder

7.7.1.1 Method

The brief tone audiometry study adheres to the General Method as described in Chapter 2. This study-specific method section describes the participants as well as the signal parameters and procedures that were unique to the brief tone study.

7.7.1.2 Participants

There were thirteen children, 2 girls (8 – 9 years) and 11 boys (7 – 17 years) that participated in this study. All the children participated in the larger study investigating auditory processing abilities in children. The clinical classification of children into APD and non-APD groups resulted in 7 children (all boys) falling into the clinical APD group (based upon 2 or more of the 5 behavioral tests of central auditory function falling more than 2 standard deviations below expectations) and 6 children (2 girls and 4 boys) falling into the clinical non-APD group. All had normal hearing sensitivity as described in the general method.

7.7.1.3 Signals & Procedure

The temporal integration task involved determination of detection threshold in quiet for signals of three different durations. For this reason the standard signals in the adaptive 3AFC task were set with an amplitude and duration equal to zero so, in essence, this represented silent periods that occurred with the graphic animation. The target stimulus was a 1000 Hz tone burst that was presented at an initial intensity of 37 dB SPL. The signal was passed through a 10 ms ramp cosine squared gating filter. The three conditions that differed in tone burst durations (256 ms, 64 ms, and 16 ms) were tested by adaptively varying the tone level. Two consecutive correct responses resulted in a reduction of the target intensity and one incorrect response resulted in a level increase. The initial step size was 8 dB SPL. Following the first reversal, the target intensity adapted by a factor of 0.5 which occurred after two consecutive correct responses, or one incorrect response. The final step size for this task was 2 dB SPL.

Thresholds for the target, adapting signal, were obtained using the adaptive three alternative forced choice oddity paradigm as described in the general method. In this task, however, the listener was asked to detect which of 3 intervals contained a sound because the standard signals were not audible (silent).

7.7.1.4 Results

Thirteen children each completed nine thirty-trial blocks to obtain three absolute threshold estimates for each of the three signal duration conditions. Thresholds were calculated for each block of trials and a repeated measures analysis of variance was conducted with the three block thresholds in each condition. The results revealed the absence of a statistically significant difference between individual block thresholds for the 256 ms signal duration condition, Pillai's Trace = 0.125, $F(2,11) = 0.785$, $p = 0.480$, $\eta^2 = 0.125$. A statistically significant difference was not found between individual block thresholds for the 64 ms signal duration condition, Pillai's Trace = 0.074, $F(2,11) = 0.440$, $p = 0.655$, $\eta^2 = 0.074$. Statistical analysis revealed the absence of a significant difference between the individual block threshold in the 16ms signal duration condition, Pillai's Trace = 0.009, $F(2,11) = 0.052$, $p = 0.949$, $\eta^2 = 0.009$. The three threshold estimates in each condition were averaged to obtain a single threshold estimate for each signal condition. Estimates of temporal integration were obtained by comparing the average threshold obtained in the 16 ms and 256 ms conditions.

Thresholds are shown for individual listeners as a function of the three signal durations, 16, 64, and 256 ms, in Figure 20. Each listener has a unique symbol. Group designation for the children is represented through colour coding. Children identified as APD are shown with blue symbols and those children that did not receive the diagnosis are shown in red. Inspection of Figure 20 gives the impression that there was a significant amount of overlap in thresholds achieved by the two groups but that the variance in performance is greater for the 16 two shortest signals. The cause of this increased variability appears to be the result of somewhat higher (poorer) thresholds obtained by the APD group. An analysis of variance was conducted to assess differences in thresholds by duration and group designation. Levene's Test of Equality of Error Variances showed that the clinical groups had equal variance in threshold scores for the 256 ms signal, $F(1,11) = 1.001$, $p = 0.339$, but that variance in threshold scores obtained by the groups was significantly different for the 64 and 16 ms signals, $F(1,11) = 15.120$, $p = 0.003$ and $F(1,11) = 11.148$, $p = 0.007$, respectively. Although the variance in performance was greater in the APD group, the differences in thresholds between the two clinical groups was not statistically significant, Pillai's Trace = 0.319, $F(3,9) = 1.406$, $p = 0.303$, $\eta^2 = 0.319$. The improvement in absolute threshold with increasing tone duration was statistically significant, Pillai's Trace = 0.992, $F(2,11)$ F = 75.891, $p = <0.001$, $\eta^2 = 0.932$. Figure 21 shows the difference threshold (defined as the difference between the 256ms threshold and the 16ms threshold) according to age and group designation. Children identified through the clinical test battery as APD and those not are represented by the blue diamond and red squares respectively. For comparison, temporal integration difference thresholds from previously published studies have been included in Figure 21. They are shown by the filled green triangles (Olsen & Buckles, 1979), filled orange circle (Watson & Gengel, 1969), and asterisk (Barry & Larson, 1974) symbols and represent means for the age groups at which they are plotted. A univariate analysis of variance conducted for the difference threshold and clinical group revealed the absence of a statistically significant difference, $F(1,12) = 0.577$, $p = 0.464$, $\eta^2 = 0.050$. It is evident, from Figure 21 that the temporal integration difference thresholds for some children in both of the clinical groups are elevated in comparison to normal adults and typically developing children but that the outliers were from the APD group. All the children who participated in the present study demonstrated elevated temporal integration difference thresholds in comparison to the children included in the Olsen and Buckles (1979) study but some of the children performed in a similar fashion to the children included in the Barry and Larson (1974) study and the adults who participated in the study by Watson and Gengel, (1969). Using these latter two studies as a comparison, there were 6 out of the 7 APD listeners and 4 of the 6 non-APD listeners who demonstrated elevated temporal integration difference thresholds as measured through the brief tone audiometry task.

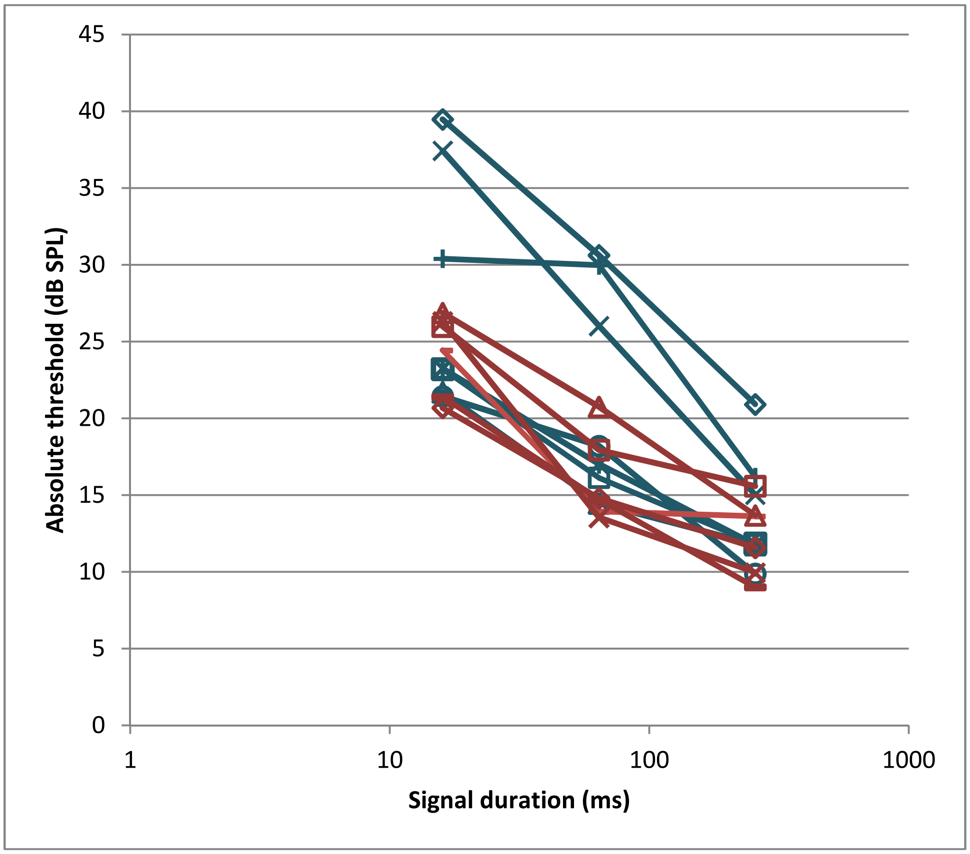


Figure 20. Absolute threshold for 1000Hz tones are shown as a function of signal duration on a logarithmic scale. Each listener has a unique symbol for threshold. Group designation is made by way of symbol and line colour. The APD and non-APD group colour is blue and red respectively.

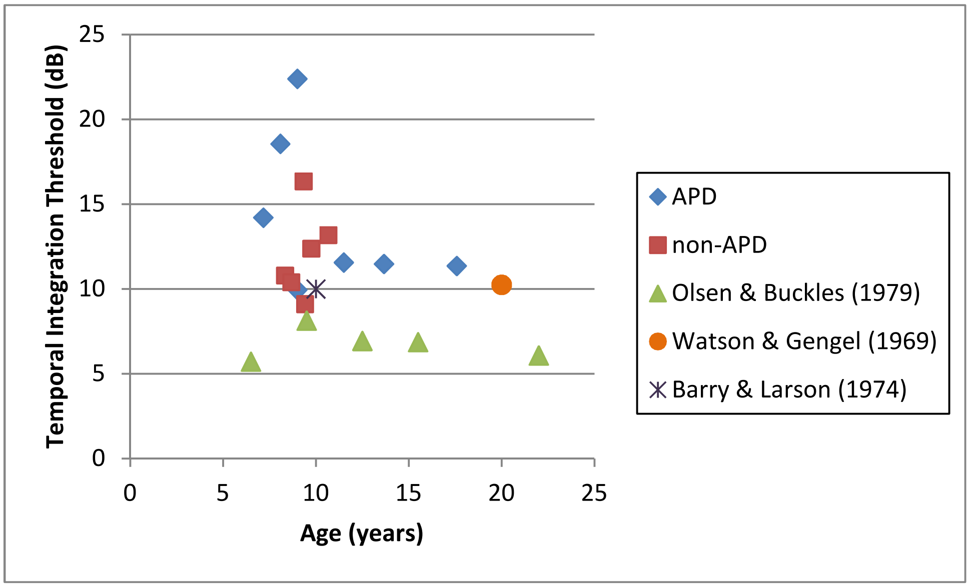


Figure 21. Temporal integration difference thresholds (16 ms threshold - 256 ms threshold) for 1000Hz signals are shown as a function of age. Diamond and square symbols represent the APD and non-APD groups respectively. The mean temporal integration difference threshold for normal adult listeners with identical signals is shown as the orange circle. Mean temporal integration difference thresholds (20 ms threshold – 500 ms threshold) in typically developing children are shown for 1000 Hz signals as the green triangles and star.

7.7.1.5 Discussion

Thresholds for brief tones were used in this study to gain some insight into the temporal integration abilities of children suspected of having auditory processing disorder. Thresholds for 1000 Hz tones were obtained from each listener for three durations, 16, 64, and 256 ms. Statistical analysis revealed that the participants in this study demonstrated a significant decrease (improvement) in threshold with the increase in signal duration and this is considered consistent with results obtained with normal adults and typically developing children. The thresholds for the study participants however were elevated in comparison to thresholds reported in past studies.

It was also noted that the thresholds for the 256 ms signal did not reach levels similar to those recorded during the pure tone testing conducted prior to entry into the study. The threshold obtained for the 256 ms signal should be similar to those obtained during the hearing assessment for two reasons. One reason is that the dB SPL and HL scales used for the 256 ms signal test and the hearing test respectively are equivalent at 1000 Hz, so the threshold obtained for the two tests should be similar. The other reason similar thresholds would be expected is that a substantial change in threshold is not expected after signals achieve a duration of 300 ms (Green, Birdsall, & Tanner, 1957; Watson & Gengel, 1969; Yost, 2007, Chapter 10). The presence of a discrepancy between the hearing test threshold and 256 ms threshold suggested the possibility that the 256 ms signal was not of sufficient duration for the children to integrate and achieve thresholds similar to those obtained during a hearing test. It is possible that best performance occurred during the hearing test because longer signals may have been provided that allowed for lower thresholds. Alternatively, it is possible that an undetected noise-floor was present during the brief tone testing and the children were unable to detect the signals in the noise-floor. It is likely that the signals used during the hearing assessment were longer than 250 ms leaving the possibility that temporal integration for this group could continue well past the 256 ms duration employed in this study. The existence of a noise-floor that interfered with signal detection was tested using a Bruel and Kjaer Hand Held Analyzer (Type 2250) and associated preamplifier (Type 2669) and coupler system

(Bruel and Kjaer 4157 Ear Simulator with integrated Type 4131 microphone). It was determined that a 17 dB SPL noise floor at 1000 Hz was being produced by the equipment being used to generate signals. This noise floor may have interfered with the ability for some of the children to detect the 256 ms signals at a level that was consistent with the 1000 Hz thresholds recorded during the hearing test. Of interest is the fact that there were two children who demonstrated thresholds for the 256 ms signals that were above this noise-floor level. The performance of these children leaves open the possibility that part of the reason for the discrepancy between the 256 ms signal threshold and the hearing assessment threshold is related to the need for longer duration signals to achieve those softer thresholds. Although the noise-floor may complicate the conclusions that can be made regarding the results of this study, it is clear from Figure 20 that for each increase in signal duration there is an accompanying decrease in threshold. So although the noise-floor may restrict the final outcome regarding temporal integration threshold, the trends are present and clear.

Although the APD and non-APD groups did not differ significantly in performance on the temporal integration task it was evident that a few of the children from the APD group demonstrated elevated thresholds. These children appear to have difficulty with the detection of very brief signals and are in agreement with the findings from the initial study of temporal integration conducted as part of this project. This is a significant finding because it confirms the impression obtained from the initial study that some children suspected or identified as having an auditory processing disorder may have difficulty with temporal integration tasks.

7.8 Summary and general discussion

In this project, the study of temporal integration was composed of two parts, one that retained a clinical focus and one that was conducted in the laboratory and included three groups of listeners. The results of the studies were similar in that several of the APD children demonstrated elevated thresholds across signal durations. There were also some APD listeners who demonstrated elevated thresholds but only for the shortest duration signals. The implications of higher than expected temporal integration thresholds are unclear. Abnormal test results typically involve the reduction of temporal integration thresholds, as seen with the hearing impaired population (Barry & Larson, 1974; Sanders, Josey, & Kemker, 1971). Thresholds that are similar to the normal population are also seen in individuals with eighth nerve lesions (Olsen, Rose, & Noffsinger, 1974; Sanders, Josey, & Kemker, 1971; Wright, 1978). To demonstrate an elevation of temporal integration thresholds the individual thresholds for signal duration must be considered because it is the difference between long and short duration signals that define the temporal integration threshold. The longest duration threshold would represent best or ideal performance of the auditory system's ability to integrate acoustic information. This threshold is considered a baseline and would not be expected to contribute to an increase in temporal integration threshold. It is an elevation of the threshold for the briefest duration signal that is likely responsible for the large temporal integration thresholds. As was evident in both studies, the thresholds for the shortest duration signals are much higher than expected for many of the children in the clinical population and confirm that this is the likely source of the increased temporal integration thresholds.

A clear understanding of the implications of a requirement for increased energy in order to detect brief signals is not readily available and the functional sequelae of such a temporal integration disorder may be even less clear. It could be hypothesized that the elevated temporal integration threshold may be an indication of a processing system that is somewhat slow and requires additional time and, or energy for the detection and recognition of signals, especially those that are at or near threshold. Goldstein and Kramer (1960) investigated temporal integration in a group of young (<40years old) and old listeners. Their results indicated that the older listeners did have temporal integration thresholds that were 2.5 to 3 dB higher than the young listeners. This finding may be evidence supporting the idea of an auditory temporal integration and processing system that is slower in children that present with these elevated thresholds as compared to children that have typical development and achieve expected integration thresholds. Although they did not include temporal integration tests in their investigation, Gordon-Salant and Fitzgibbons (1993) investigated temporal factors and speech recognition in young and older listeners with and without hearing loss. They found that the older listeners with normal hearing sensitivity had slower temporal processing abilities in comparison to the young listeners and that these reduced temporal abilities were correlated to reduced performance on degraded speech recognition tasks. They conclude that an age-related change to the auditory system contributes to slower temporal processing and in turn, difficulty understanding degraded speech signals. It may be the case, for children suspected of having auditory processing deficits that their auditory system is similar to the slower processing system seen in older individuals and that this is what is contributing to their atypical temporal integration thresholds.

A clear understanding of the exact nature of temporal integration in the clinical population remains elusive. The results of the present study demonstrated that children in the clinical population do experience an improvement in detection threshold with an increase in signal duration. Unfortunately the question of whether maximum integration of the signal is achieved by 300 ms remains unanswered. There is clear evidence that some children in the clinical population have elevated thresholds for brief signals and elevated temporal integration thresholds. The elevated temporal integration thresholds are likely due to elevated detection thresholds for the shortest duration signals, or possibly that the children are unable to complete this kind of listening task. The elevated temporal integration thresholds pose some interesting questions, however, about what factors may be contributing to the listening difficulties these children are experiencing and the functional outcomes of impaired temporal integration. Further research in this area would be able to provide some insight into these questions and issues. Future direction may include a study that includes a variety of signals and possibly the use of Auditory Brainstem Response (ABR) assessment for physiologic correlates to the behavioural thresholds. The ABR is a sensitive test of auditory nerve and brainstem function and synchrony (Hood, 1998) so any abnormalities in the temporal integration functions may be reflected in the neural recordings made during ABR testing. Amplitude and or latency recordings of the ABR may vary if temporal integration does not occur in a normal fashion. It would be beneficial to compare ABR and temporal integration function slopes to determine if there may be a relationship in these values. Further investigation into the effects of extreme signal durations, either very short or very long, may also be informative in isolating some of the underlying mechanisms involved in temporal integration.

Chapter 8

8 Project Summary & Discussion

Normal hearing sensitivity and good auditory perception are essential for speech-language development and learning. Auditory perception, as measured through the ability to resolve and discriminate acoustic signal features, has been shown to be a problem for some children with diagnosed learning disability, specific language impairment, dyslexia, or attention disorders. Although the evaluation of discrimination abilities as part of an auditory processing test battery has been recommended (ASHA, 2005a; AAA, 2010), to date there are few commercial tools available for the audiologist to accomplish this task (AAA, 2010; Bellis, 2006, Chapter 4). The investigation of encoding abilities, such as signal feature discrimination or resolution, has taken place in the laboratory with normal adults, but only a few studies have been conducted with children considered at risk for or diagnosed with an auditory processing disorder. Therefore, the purpose of this project was to investigate signal encoding abilities in children suspected of having an auditory processing deficit.

All children who participated in the project had been referred for an assessment of their auditory processing skills. The decision to assess the clinical population referred for assessment meant that each child was reported to have listening/auditory problems in the classroom and/or at home along with some level of academic failure. There was an expectation, however, that not all children would be identified as having an auditory processing disorder. It is not an uncommon occurrence to have children who present with behaviours suggesting the presence of an auditory or listening problem obtain test scores within the expected range for their age on a clinical auditory processing test battery. Possible reasons for this may include presenting problematic behaviours that are similar to or associated with other disorders, a misunderstanding that auditory skills and abilities are the reason for the observed concerning behaviours in the classroom, or the possibility that the clinical measures may not have been sufficient to identify an existing auditory processing deficit. The inclusion of the clinical population in this project allowed for an opportunity to investigate not only the signal encoding abilities in those children identified as APD but also those suspected of having APD but that did not receive the diagnosis based on the outcome of a typical clinical test battery. All participants in the project demonstrated normal hearing sensitivity. The children participating in this project exhibited a typical clinical population composition in regards to age distribution and gender representation. The boys outnumbered the girls by a factor of at least two-to-one in the groups of listeners for all studies included in the project. The average age of the children participating in the project was 9.8 years. Children were designated as APD or non-APD based on diagnosis that was made in accordance with recommended clinical protocol, following completion of the clinical auditory processing test battery. In all but the frequency resolution study that had 3 times as many APD as non-APD listeners, each study had equal numbers of APD and non-APD listeners.

To assess the signal encoding abilities of children suspected of having an auditory processing disorder a three alternative forced choice task presented with graphics in a game-like format was employed. A 2-down, 1-up adaptive procedure with feedback was combined with the alternative forced choice game format as a way to encourage attention to the task and the successful acquisition of reliable thresholds. Because sound is composed of spectral, level, and temporal features, a series of five studies was designed to represent each of these signal feature categories and allow for a sampling of the encoding abilities of the clinical population of children. The series of studies included the evaluation of frequency resolution, frequency discrimination, intensity discrimination, temporal resolution and temporal integration in the clinical population. To provide consistency, optimize performance, and allow for the opportunity to make comparisons across tasks, a 1000 Hz signal was employed as the test frequency for each of the five encoding tasks. A total of 59 children participated in this project. Unfortunately each listener did not complete every listening task. A total of 38 children completed only one study, either the frequency discrimination task or the frequency resolution task. Only 12 children completed all five studies. A temporal integration task was also conducted with three groups of listeners that had not participated in the other signal encoding tasks.

8.1 Performance variability

Performance by the clinical population on the signal encoding tasks was highly variable. Variability in thresholds within each study ranged from normal to outlier performance. Performance between studies was also considered highly variable because for some signal feature encoding tasks participants achieved extreme outlier performance whereas on other tasks this was not the case. For example, performance in the frequency discrimination study ranged from normal threshold values to thresholds that were ninety times the expected value but in the intensity discrimination study the outlier performance was only as great as twelve times the expected threshold value. The implications or meaning associated with the differences in variability across tasks is unknown. Differences across studies may be due to individual differences in listeners or differences related to the signal feature being encoded. Determination of the cause for the differences in variability across tasks would require further investigation.

There were differences in the threshold variability observed between the two groups of listeners, those with and without a clinical designation of APD. Variability was greater in the APD group of listeners in comparison to those children without the diagnosis in the frequency discrimination, intensity discrimination, frequency resolution, and temporal integration studies. This was a statistically significant finding. No differences were present between the two groups in the temporal resolution gap detection study. Because young children and children with learning, speech-language, or attention problems tend to demonstrate more variable performance than the normal population, it was not unexpected to find a high degree of variability in the signal encoding thresholds obtained in the listeners participating in this project. The project participants were all children from a clinical population of individuals experiencing academic failure and displaying behaviour that suggested listening or auditory processing problems. The discovery of greater variability in the APD population is also not surprising since by definition these children had already been identified through the clinical battery of auditory processing tests as having difficulty with auditory related tasks.

Only one test, frequency discrimination, provided the opportunity to explore the effect of threshold change with age. In this project, a decrease in threshold with increasing age was evident in the frequency discrimination threshold results. Published literature in the area of frequency discrimination abilities have indicated a somewhat longer developmental trajectory than for the other tests included in this project. Therefore the decrease in threshold with increasing age was in keeping with previously published reports. It should be noted however that the variability introduced into the threshold data by this developmental trend was dwarfed in comparison to the variability present in the range of threshold data.

8.2 Signal feature encoding

On an individual and group basis, the children that participated in this project experienced varying degrees of difficulty with the five signal encoding tasks. The specific number of children demonstrating thresholds outside the expected range varied across task. The best performance by children participating in the project was seen for the intensity discrimination task where only two listeners demonstrated outlying thresholds and the remaining children demonstrated thresholds that were either expected for their age or only slightly elevated. Significant numbers of listeners demonstrated difficulty with the spectral and temporal encoding tasks. Elevated and outlying thresholds for signal encoding tasks were not restricted to the APD group. Although the largest numbers of children demonstrating poor performance on the encoding tasks were those in the APD group, there were also members of the non-APD group that demonstrated poor performance and/or outlying thresholds. On the basis of these results, it was concluded that auditory processing disorder can include poor spectral and/or temporal signal encoding ability in some children. It is also possible, as seen in this project, that the assessment of signal encoding ability may be the only behavioural indication of an auditory processing disorder in some children in the clinical population.

There were twenty-one children that completed more than one listening task but not all five studies. There were twelve children in total that completed all five of the listening tasks. This number of participants was too few to conduct a statistical analysis of performance trends across signal encoding tasks. A specific trend suggesting an association of performance outcome on one task with others was not clearly evident in the data obtained as part of this project. For the twelve listeners that completed each study in the project all scored beyond the expected values for at least two tasks. Three children ranked within the five poorest performers for each of the five tasks. Two of these had threshold scores outside of the expected values for all five tasks and one scored outside of normal range on four of the tasks. Although there did not appear to be consistency across performance, there was no way to show this conclusively due to the limited numbers of children that completed all five studies.

8.3 Trial-by-trial analysis

In addition to the threshold values obtained in each study included in the project there was also qualitative information about the nature of the poor performance that could be gleaned through the trial-by-trial data in blocks of trials. When the trial-by-trial data in a block were plotted, there were four different patterns that emerged. These patterns provided some qualitative information about the threshold and or response behaviour of the listener. Similar to the study conducted by Moore, Ferguson, Halliday, and Riley (2008), good performance that achieved normal threshold values, genuine poor performance tracking, and inattentive threshold tracking were evident in the data obtained from the listeners participating in this project. An unexpected trial-by-trial tracking pattern was observed in this project. This tracking pattern appeared to be a mixture of blocks with good performance and effective threshold tracking that achieved normal or close to age appropriate thresholds, and blocks of genuine poor performance where the threshold was not age appropriate. It appeared that these children were varying their response criterion from one block of trials to the next with the overall result being an elevated or outlying threshold value, even though the children demonstrated the ability to achieve a normal threshold value. One reason for this kind of change in decision criteria could be postulated as learning. If the initial block of trails produced poor performance with an elevated threshold and subsequent blocks of trials resulted in improved thresholds then learning may be a cause for the change in decision criteria. Although some of the listeners that displayed differences in block threshold showed a change in decision criteria that could suggest learning, this was not the case for all listeners. It could be postulated that the pattern was a result of equipment failure however problems with the equipment was not noted during any of the listening checks or while monitoring the children during the task. Although the cause for this particular pattern of responding is unknown, it is clear that the trial-by-trial data is an important element in the ability to interpret the signal encoding test results. The trial-by-trial tracking can provide qualitative information about the nature or cause of poor performance that is critical for the accurate interpretation of the test results. Differing trial-by-trial patterns of performance were seen across studies and in both the APD and non-APD groups. Poor performance by children in the clinical population can be the result of poor signal encoding abilities, inattention, or reasons not yet clearly understood.

8.4 Clinical implications

The findings from this project revealed that the children in the APD group, those children who would be identified clinically as having auditory processing disorder, demonstrated the greatest amount of variability in performance and tended to include the performers that were outliers or displayed the poorest performance. For children who would have been diagnosed as not having an auditory processing disorder, the variability in psychoacoustic task thresholds was smaller than in the APD group but there continued to be children who performed outside the expected range on these tasks, suggesting that they were experiencing difficulty accurately and efficiently encoding signal features. No listening task was immune to the finding that, regardless of how they were grouped, some children performed within expectations and some demonstrated thresholds that suggested difficulty encoding the signal feature being assessed. At this point in time, there is no opportunity to assess a variety of signal encoding abilities in the clinic so children who have poor signal encoding may go unidentified if they achieve age appropriate auditory processing abilities on the clinical test battery. For the children who have signal encoding problems but go unidentified as having an auditory processing disorder the problem goes untreated and the children continue to struggle with understanding auditory information. For children with an APD diagnosis the signal encoding problem would also go undiagnosed and untreated. Although APD management strategies were implemented for these children they may be insufficient and listening difficulties would persist. The first step towards addressing the signal encoding needs of these children begins with identification during the clinical assessment.

The question frequently faced by clinicians is whether the reported difficulties being experienced by a child in the classroom are the result of an auditory processing disorder or a general attention disorder. The opportunity to assess signal encoding ability in children also provides a small window of opportunity to address attention. Moore, Ferguson, Halliday, and Riley (2008) recently demonstrated that the review of trial-by-trial tracking of the target stimulus by a listener can differentiate between the good signal encoders, poor signal encoders and inattentive listeners. The somewhat restricted threshold tracking seen for the genuine poor performer suggests that threshold is being estimated in an appropriate fashion but that the threshold is elevated. The threshold tracking by the inattentive performer is not systematic. Responses have a large range and there appears to be no focus or narrowing to a threshold centred search. The benefit of this kind of data review is that the inattentive listeners can be redirected into more appropriate assessment and intervention streams. The option for reassessment is available at a later date if auditory skills continue to be questioned for these inattentive listeners. Poor performers can be further assessed to determine the exact nature of their signal encoding difficulty and supported with appropriate habilitation options. In this study, a fourth pattern of trial-by-trial performance was identified and was postulated to involve a change in response decision criterion. Whether this pattern of responding is related to an auditory perceptual, attention, or some other unidentified problem is not yet known and further investigation will be required to determine the way in which it should be interpreted when found. The benefit of the trial-by-trial data analysis is that it offers some insight into the potential identification of those children for whom general attention and the inability to focus on the task is the biggest obstacle. At the present time the ability to identify the children with attention problems is not possible with a typical clinical battery of auditory processing tests.

8.5 Signal feature encoding as part of a clinical auditory processing assessment

The results of this project revealed that some children suspected of having an auditory processing disorder experience poor signal feature encoding. Children in both the APD and non-APD groups demonstrated signal encoding performance below expectations. Each child that completed all five tasks demonstrated performance falling below expectations on a minimum of two signal feature encoding tasks and some children demonstrated difficulty with all five tasks. Therefore it would appear that the results of this project show that signal feature encoding can be impaired in the clinical population and these tests should be included in an assessment of auditory processing abilities as recommended by ASHA (2005a).

The inclusion of signal feature encoding tests into the assessment battery would address the void that presently exists in the assessment of auditory discrimination and the use of non-speech stimuli in the battery. The evaluation of signal encoding during an assessment of auditory processing provides additional insight into the abilities of the listener and the eventual tailoring of habilitation measures. At the present time there are a few temporal resolution tests, in the form of gap detection, that are available on the market for clinical use. The Auditory Fusion Test – Revised is one such test that has been available for several years. This test is composed of a series of pre-recorded stimuli that have been useful for the assessment of temporal resolution but the test is long and attention may become a confound in the completion and interpretation of the results for such a test. Recently, attempts have been made to improve the test method for gap detection but there has been little progress in the advancement of signal feature encoding assessment into the clinical setting (Emanuel, Ficca, Korczak, 2011). Because the adaptive method used in this study would be appropriate for use in a clinical setting, and technology has now advanced to the point where signals can be generated without expensive and bulky hardware, an experiment was conducted to assess the usefulness of the adaptive procedure (based on laboratory methods) in comparison the a clinically available test of temporal resolution.

8.6 Comparison of two Gap Detection tests

The purpose of this comparison study was to determine the utility of an adaptive, three alternative forced-choice, psychoacoustic task for the assessment of signal encoding abilities in a clinical setting. To accomplish this, performance on the 3AFC psychoacoustic task and a test that is presently used in the clinical setting were compared in a group of normal and a group of APD children. Because gap detection, an acoustic temporal resolution signal encoding task, is available in a format for use in the clinical setting the comparison of children's performance on the two tasks was conducted for gap detection thresholds. The Auditory Fusion Test, Revised (AFT-R), a clinically available test of gap detection using tonal stimuli (McCroskey & Keith, 1996) and a 3AFC adaptive gap detection psychoacoustic task were employed in this comparison study. It was hypothesized that no statistically significant difference would be observed for the within subject gap detection thresholds obtained for the two measures.

8.6.1 Method

8.6.1.1 Ethics Approval

Approval of this project was secured from the University of Western Ontario, Office of Research Ethics (Appendix C). Parents were required to read the study Letter of Information and sign a consent form for study participation prior to the child's enrollment in the study (Appendix D). Verbal assent was obtained from each child at the beginning of the study and continued to be obtained from the participant on an ongoing basis in advance of each measure or activity during the test sessions. There was no penalty for withdrawal from the study.

8.6.1.2 Participants

School-aged children were recruited from London, Ontario and the surrounding area by way of a letter of information that invited typically developing children and children with an auditory processing disorder to participate in the research project. To be enrolled in the study, all participants were required to demonstrate normal pure tone thresholds and middle ear function (ASHA, 1994). If a child was excluded from the study due to hearing loss and/or middle ear dysfunction, their parents were informed of their child's hearing assessment results and they were referred to the appropriate community professionals for follow-up.

A total of 22 children were recruited for the study. One group of children were normally developing children (defined as experiencing no academic difficulties at school, the absence of any behaviour that would suggest listening skill deficits, and no parental concern regarding academic and general developmental progress), and included 10 males and 4 females, ranging in age from 7 to 14 years. The second group of children was diagnosed with, or was suspected as having an auditory processing disorder and included 8 children, 5 males and 3 females ranging in age from 8 to 13 years. To be included in the study the children suspected as having an auditory processing deficit completed two clinical auditory processing tests, the Staggered Spondaic Word Test (Katz, 1998) and the Pitch Pattern Sequence Test (Pinheiro, 1977). The APD group inclusion criteria were established in accordance with the criteria for APD diagnosis recommended by Chermak and Musiek (1997, Chapter 4). Allocation into the APD group was made if a participant failed one of the auditory processing tests by greater than three standard deviations below the age mean or failed both tests by greater than two standard deviations below age mean.

8.6.1.3 Procedure

All testing was completed at The University of Western Ontario Child Hearing Research Laboratory. Testing began with hearing screening and central auditory testing. Following that, participants were entered into the study and completed two blocks each of gap detection via forced-choice psychoacoustic testing and two blocks of the Auditory Fusion Test-Revised.

8.6.1.4 Hearing Assessment

Participants sat comfortably in an IAC double-walled sound isolation room (controlled acoustical environment). Conventional audiometry with an Interacoustics AC40 Clinical Audiometer was conducted to obtain pure tone thresholds for 500, 1000, 2000, and 4000 Hz. bilaterally. Signals from the AC40 were routed through Etymotic Research EAR 5A Insert Earphones coupled to the ear with sponge insert eartips. The participant then sat comfortably in a quiet room adjacent to the sound isolation rooms for the assessment of middle ear and outer hair cell function. The Grason Stadler Tympstar diagnostic middle ear analyzer assessed middle ear function for both ears by obtaining tympanograms as well as ipsilateral and contralateral acoustic reflexes at 500, 1000, and 2000 Hz.

8.6.1.5 Auditory processing tests

Two commercially available auditory processing tests, the Staggered Spondaic Word Test (SSW) and the Pitch Pattern Sequence Test (PPS), are commonly used in audiology clinics as part of an auditory processing test battery and were used to evaluate children for the presence of clinically defined (central) auditory processing disorders. These tests were selected because of their general clinical acceptance as reliable and sensitive tests for the assessment of auditory processing abilities and because they offered testing with both a speech and non-speech signals. The SSW and the PPS were administered and scored according to instruction manuals. The test order was balanced so that half of the children completed the SSW first and the other half completed the PPS first. The SSW and PPS compact disc recordings were played in a JVC XL-Z232 Compact Disc Player. Children were comfortably seated in an IAC double walled sound isolation room across from the examiner who could be viewed through the isolation room window. Auditory signals from the CD player were presented at the recommended levels by way of the Interacoustics AC40 Clinical Audiometer. The signals leaving the audiometer were heard by the participants through Etymotic Research EAR 5A Insert Earphones coupled to the ear with sponge insert eartips. The test instructions were provided as dictated by the instruction manual through the earphones by way of the AC40 talk forward capabilities. Further explanations of the test and response requirements were provided if requested or required by the participant. Tests were administered in sequence which provided a short break between tests as the CDs were changed and the audiometer adjusted as required for accurate test presentation. During this break children were reassured and encouraged to continue their good work.

Upon completion of the SSW and PPS, the tests were scored to confirm group allocation. Chermak and Musiek (1997, Chapter 4) recommended that a diagnosis of APD be made if a single test result fall greater than 3SD below the age mean or if 2 or more test scores fall greater than 2SD below the age mean. For this study a child was assigned to the APD group if their test scores met one of the following three conditions:

- one of the SSW competing condition scores fell greater than 3SD below age expectations
- one of the PPS test scores fell greater than 3SD below age expectations
- at least one of the SSW competing conditions scores fell greater than 2SD below the age expectations AND one of the PPS test scores fell greater than 2SD below age expectations

8.6.1.6 Gap Detection Tasks

The experimental portion of the study was initiated following hearing screening and, when necessary, clinical tests of auditory processing. The order of administration of the AFT-R and the adaptive 3AFC psychoacoustic gap detection task was balanced and determined by order of enrollment.

The adaptive 3AFC psychoacoustic gap detection task involved the identification of the narrowband noise signal in a group of three that contained a temporal gap. Stimuli were Gaussian noise samples of 400 ms duration separated by a 400 ms inter-stimulus interval. All stimuli were bandpass filtered with a centre frequency of 1000 Hz and a bandwidth of 400 Hz. Butterworth coefficient filtering was used to create a second order Biquad filter. The 3 samples were divided into two standard signals that did not contain a gap and one target signal that contained the gap located in the centre of the stimulus. A linear gating filter was used to ensure severe gap edges. As the gap size changed each half of the signal was shortened by the duration of half the gap size. This ensured that each of the three signals had identical 400 ms durations and that the gap was located in the centre of the target stimulus. Finally, each 400 ms stimulus passed through a Cos2 filter. The target and standard stimuli were presented at a constant intensity of 40 dB Spectrum Level (73 dB SPL). To mask spectral splatter resulting from the insertion of the gap within the target stimuli, a continuous Gaussian notch-filtered masking noise with a centre frequency of 1000 Hz and a notch width of 400 Hz was presented at 25 dB Spectrum Level (58 dB SPL).

Level calibration was conducted acoustically through the experimental set-up prior to the initiation of the study and then routinely throughout the duration of the study. Calibration was completed with a Bruel and Kjaer measuring amplifier (Type 2610) and associated preamplifier (Type 2639 with Adaptor DB1021), microphone (Type 4144), and artificial ear (Type 4152).

A Dell Dimension 8100 desktop computer with the Tucker Davis Technologies (TDT) System 3 RP2 realtime signal processor digitally generated the psychoacoustic gap detection acoustic stimuli and controlled the adaptive procedure. The Dell computer and TDT System were located outside the IAC sound isolation room to reduce the amount of listener exposure to equipment noise during the test session. The signals were digitally generated with a 50 kHz sampling rate and processed through a 24 bit Sigma Delta digital-to-analog converter. The signal output from the HB7 headphone driver was connected, through the patch panel, to an Etymotic Research ER-3A transducer earphone located in the sound isolation room where the listener received the test signals. An elo Touchsystems 15"CRT Touchmonitor Model 1525C was used to display the psychoacoustic task graphic images associated with the acoustic signals and to record the participants' responses to the stimuli when they touched the image they believed represented the target stimulus.

Gap detection thresholds were estimated using an adaptive 3 alternative forced choice paradigm with feedback. This method of obtaining psychometric thresholds has been used extensively with children and adults. Instructions for the task are simple and easily understood by children. The gap length in the target (different) stimulus was varied using a two-down, one-up adaptive procedure as described by Levitt (1971), tracking the 70.7% correct response level. Gap duration is reduced after two consecutive correct responses or increased following one incorrect response. Starting gap duration of the target signal was 40 ms, a gap size expected to be easily detected by all listeners. Gap size was varied adaptively with an initial step size of 15 ms to the first reversal. Each subsequent reversal resulted in an increase or decrease of the target gap size by a factor of 0.5 until gap size reached 2ms at which point it remained constant for the remainder of that block. The first reversal point was not included in the threshold calculation.

The forced choice paradigm employed in this study was presented in a video game format similar to the one developed by Wightman, Allen, Dolan, Kistler, & Jamieson (1989). A number of different animated and colourful graphics were available to assist in maintaining participant interest in the task. During each trial, the listener was presented with a 3 item visual graphic on the touchscreen monitor. Graphics included flowers, rain clouds, fish, clowns, or balloons in the foreground and the background was a scene appropriate to the item in the foreground or a solid colour with no graphics. Initiation of every trial was clearly indicated by the sequential appearance of the three identical foreground graphic items. In succession, each graphic changed colour or animation to indicate signal presentation (one target and two standard signals). The listener's task was to touch the graphic they believe corresponds with the target signal presentation. Target stimulus was presented in either the first, second, or third position and the computer employed an a priori probability of 0.33. Following the listener's selection, feedback was provided for that trial. The graphic items then exit the screen, clearly marking the end of the trial at which point the next trial would commence. For each block of trials a small indicator would track progress by moving from right to left horizontally or from bottom to top vertically, allowing the children to easily identify how far they had advanced in the task.

During psychoacoustic testing the listener and examiner were seated comfortably at a small table in the sound isolation room. The touchscreen monitor was located on the table facing the listener. The listener was instructed that their task was to watch the monitor, listen carefully and then touch the graphic on the monitor that "sounded different". An Etymotic Research ER-3 earphone with a foam-tip coupler was placed in the listener's right ear and an E.A.R. soft regular size earplug was placed in the left ear to reduce the interference of any possible extraneous HVAC noise during the test session. Listeners completed two blocks each (30 trials in every block) of the gap detection task. Participants had a scheduled break during the session between the gap detection measures and were allowed to take breaks upon request.

Thresholds were calculated upon completion of trial blocks from the midpoints between the reversal points for each block of trials. Trial blocks were considered for threshold calculation if a minimum of 4 reversal points were achieved. If the reversal point criteria had not been met additional blocks of trials could have been completed however, in this study, all participants achieved a minimum of 4 reversals on all trial blocks.

The Auditory Fusion Test – Revised (McCroskey & Keith, 1996) is a commercially available gap detection test. The compact disc has a series of prerecorded tone pairs with an inter pulse interval that varies systematically in an ascending and descending fashion between 0 and 40 ms in the standard version and between 40 and 300 ms in the expanded version. Five different frequency conditions are included in the standard version of the test.

The Auditory Fusion Test – Revised (AFT-R) compact disc recording was played in a JVC XL-Z232 Compact Disc Player. Auditory signals from the CD player were administered to the participants according to the test protocols and at the recommended levels by way of the Interacoustics AC40 Clinical Audiometer. The signals leaving the audiometer were heard by the participants through Etymotic Research EAR 5A Insert Earphones coupled to the ear with sponge insert eartips.

Children were comfortably seated in an IAC double walled sound isolation room across from the examiner who could be viewed through the isolation room window. The test instructions were provided as dictated by the instruction manual through the earphones by way of the AC40 talk forward capabilities. Further explanations of the test and response requirements were provided if requested by the participant. The AFT-R was administered as dictated by the test manual with the exception of the number of frequency conditions. In order to approximate the psychoacoustic task administration, the AFT-R 1000 Hz frequency condition was administered twice to the right ear. In response to the stimulus item the listener had to indicate verbally whether he/she heard one or two tones. Ascending and descending thresholds were calculated according to the instruction manual and then averaged to obtain the gap detection threshold. If children failed to obtain an ascending or descending threshold a third test was completed. The AFT-R was not administered to any participant more than 3 times.

8.6.2 Results

Twenty-two children completed two blocks (30 trials each) of the adaptive 3AFC psychoacoustic gap detection test allowing for two threshold estimates. All participants obtained a minimum of four reversal points during each threshold search. The maximum number of reversal points for a block of trials was twelve. The average number of reversal points for a block of 30 trials in this group of children was six. The estimated threshold for each block of trials was calculated by averaging the midpoints between the reversal points. Figure 22 shows the first block threshold plotted as a function of the second block threshold for each participant. The typically developing children are represented by open red square symbols and the APD group is represented by the open blue diamond symbols. Inspection of Figure 22 revealed that a number children achieved a slightly smaller gap threshold on the second block of trials. The repeated measures analysis of variance confirmed that impression. The first block of trials achieved a mean (standard deviation) gap threshold of 8.9 (1.6) ms and for the second block the threshold was recorded slightly smaller at 7.7 (2.5) ms. The repeated measures analysis of variance confirmed that the slight improvement in threshold was significant, Pillai's Trace = 0.176, $F(1,21) = 4.475$, p=0.047, $\eta^2 = 0.176$. This slight improvement in threshold is likely due to procedural learning. Although the difference in block thresholds weas significantly different the difference was considered a small learning effect that might typically be encountered in the clinical setting so the thresholds were averaged for subsequent comparisons. Average gap detection thresholds are shown as a function of age in Figure 23. The APD and typically developing groups are represented by the open blue diamond and open red square symbols respectively. A developmental trend was not evident in the threshold plot. A univariate analysis of variance was conducted to compare the average gap detection thresholds between the typically developing and APD groups. Levene's test of equality of error variances revealed that the variance in the two groups was not significantly different, $F(1,20) = 0.177$, $p = 0.678$. The mean (standard deviation) threshold for the APD and typically developing groups was 8.1 (2.2) ms and 8.3 (1.6) ms respectively and were not found to be significantly different, $F(1,20) = 0.072$, $p = 0.791$, $\eta^2 = 0.004$.

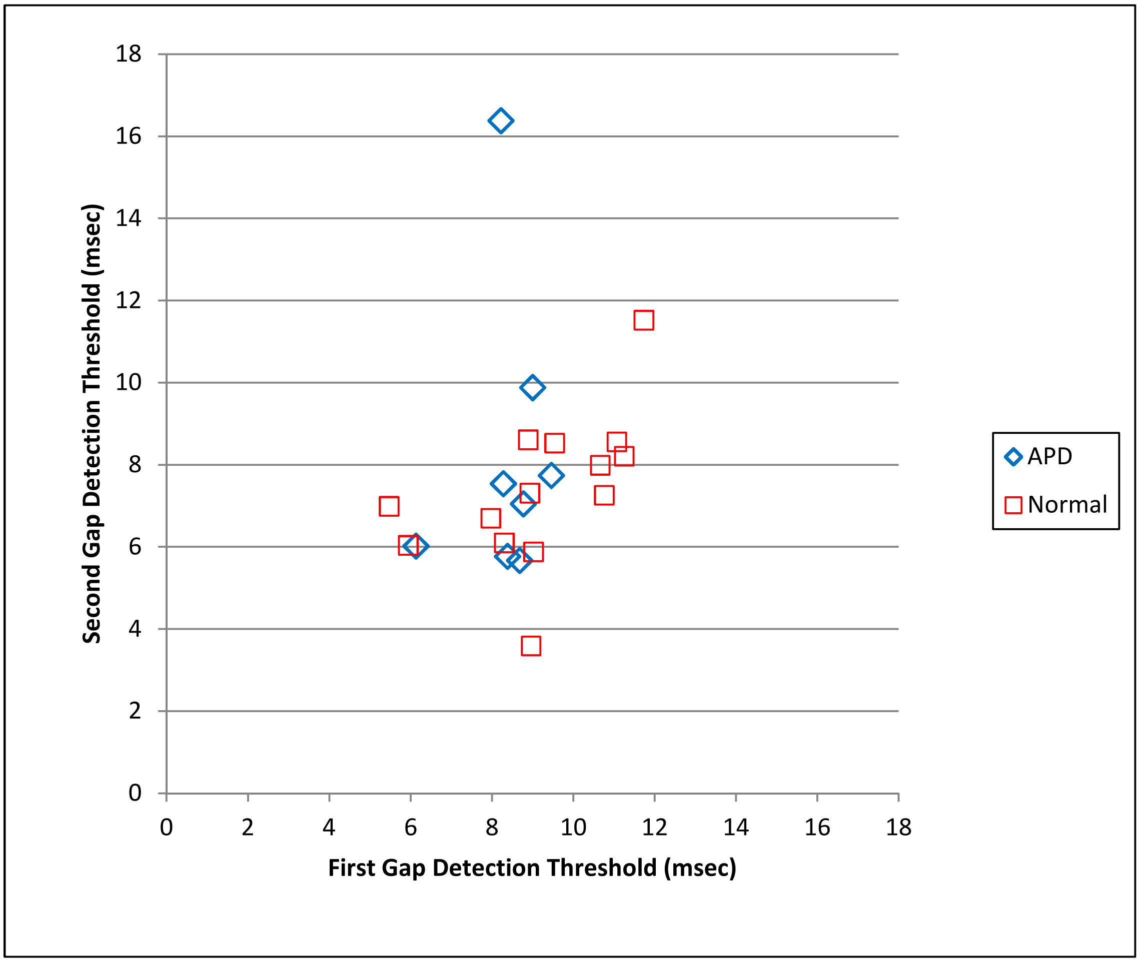


Figure 22 Comparison of the gap detection threshold obtained on the first block of trials as a function of the gap detection threshold obtained on the second block of trials. The children identified with an auditory processing disorder are represented with the open blue diamonds. Typically developing children are represented by the open red squares.

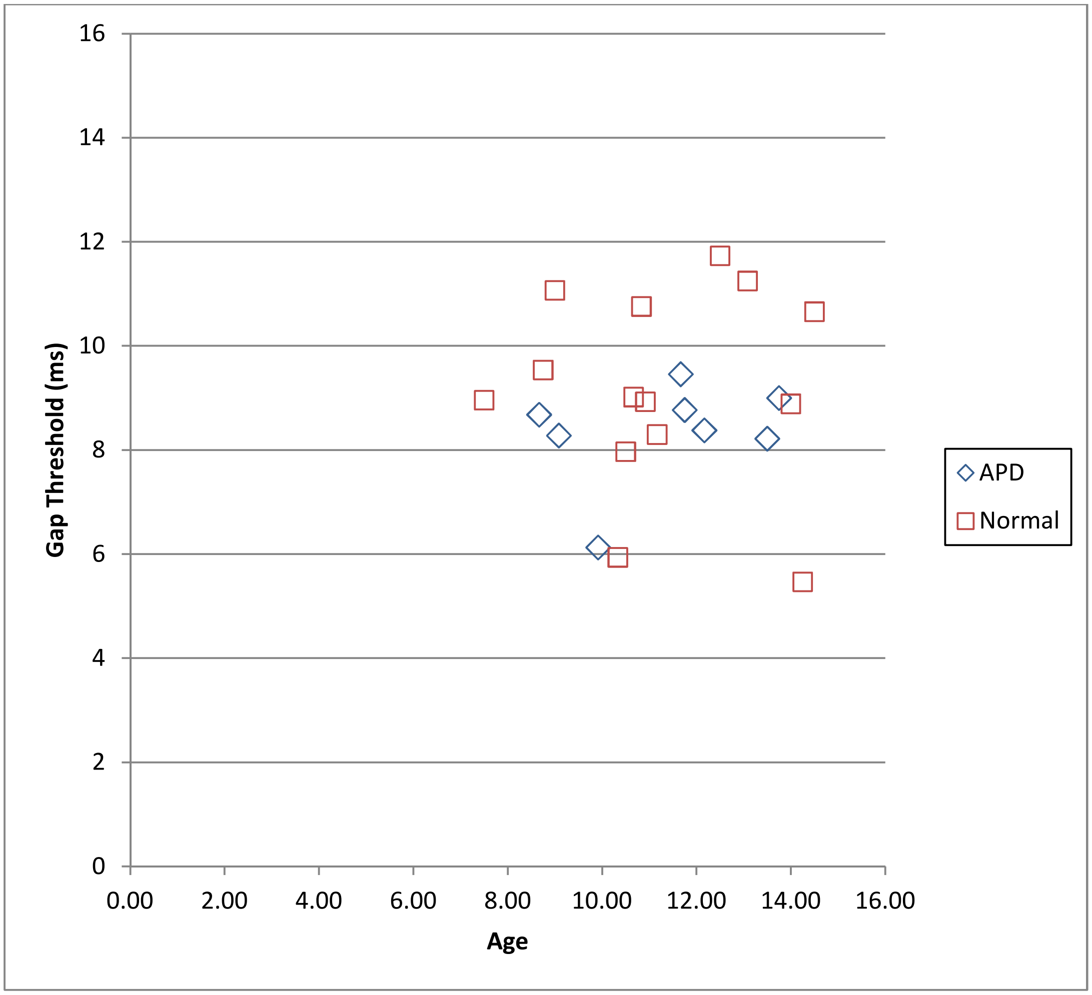


Figure 23 Average gap detection thresholds are shown as a function of age. The children identified with an auditory processing disorder are represented with the open blue diamonds. Typically developing children are represented by the open red squares.

The children completed at least two searches for AFT-R fusion thresholds at 1000 Hz. Fusion points were determined, according to test specifications, for both the ascending and descending series and thresholds were calculated as an average of the two fusion points. A third search was completed only if there was a failure to obtain a fusion point for one or both series. There were five children who, after three attempts, did not achieve an ascending and/or descending fusion threshold resulting in an inability to calculate the average AFT-R. Two of these children were part of the APD group and three were part of the normal group. These participants were excluded from analysis of AFT-R thresholds. For the remaining 17 listeners, AFT-R threshold estimates are shown in Figure 24. In Figure 24, the first AFT-R threshold is plotted as a function of the second threshold. The APD group is represented by the open blue diamond symbols and the typically developing group is represented by the open red square symbols. The thresholds derived from the first and second block appeared similar. Average thresholds were 18.5 ms (SD = 28.5) and 18.1 ms (SD = 26.8) for the first and second tests respectively. A repeated measures analysis of variance revealed that the two tests were not significantly different from one another Pillai's Trace = 0.014, $F(1,16) = 0.225$, $p = 0.641$, $\eta^2 = 0.014$. Thresholds were averaged for further analysis. Average thresholds, plotted as a function of listener age, are shown in Figure 25. The APD and typically developing groups are represented by the open blue diamond and open red square symbols respectively. A developmental trend was not evident in the plot of AFT-R thresholds. A univariate analysis of variance was conducted with average AFT-R thresholds as the dependant variable and group allocation as the independent variable. Levene's test of equality of error variances revealed that the two groups did not have significantly different variances, $F(1, 15) = 1.830$, $p = 0.196$. The mean (standard deviation) thresholds for the APD and typically developing groups were 21.2 (38.7) ms and 16.7 (21.5) ms respectively and were not found to be significantly different, $F(1,15) = 0.009$, $p = 0.757$, $\eta^2 = 0.007$.

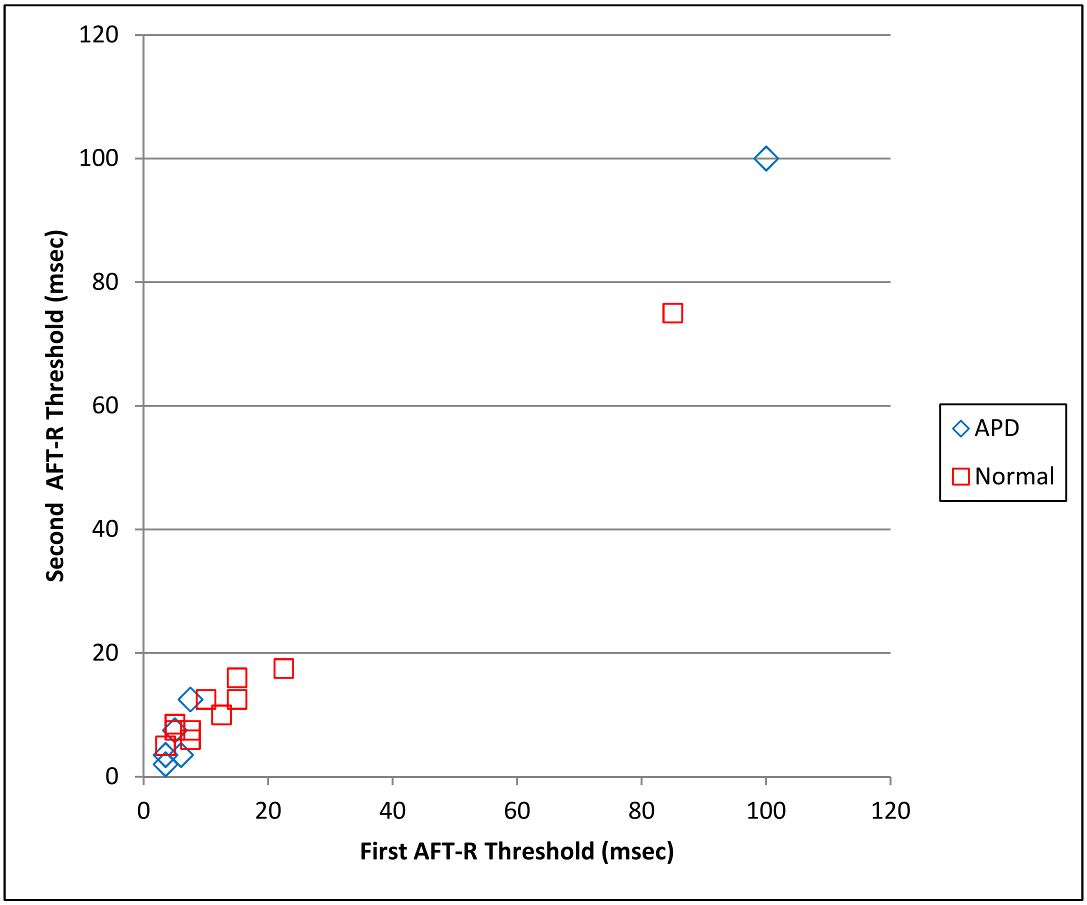


Figure 24 Comparison of the AFT-R fusion threshold obtained on the first test as a function of the AFT-R fusion threshold obtained on the second test. The children identified with an auditory processing disorder are represented with the open blue diamonds. Typically developing children are represented by the open red squares.

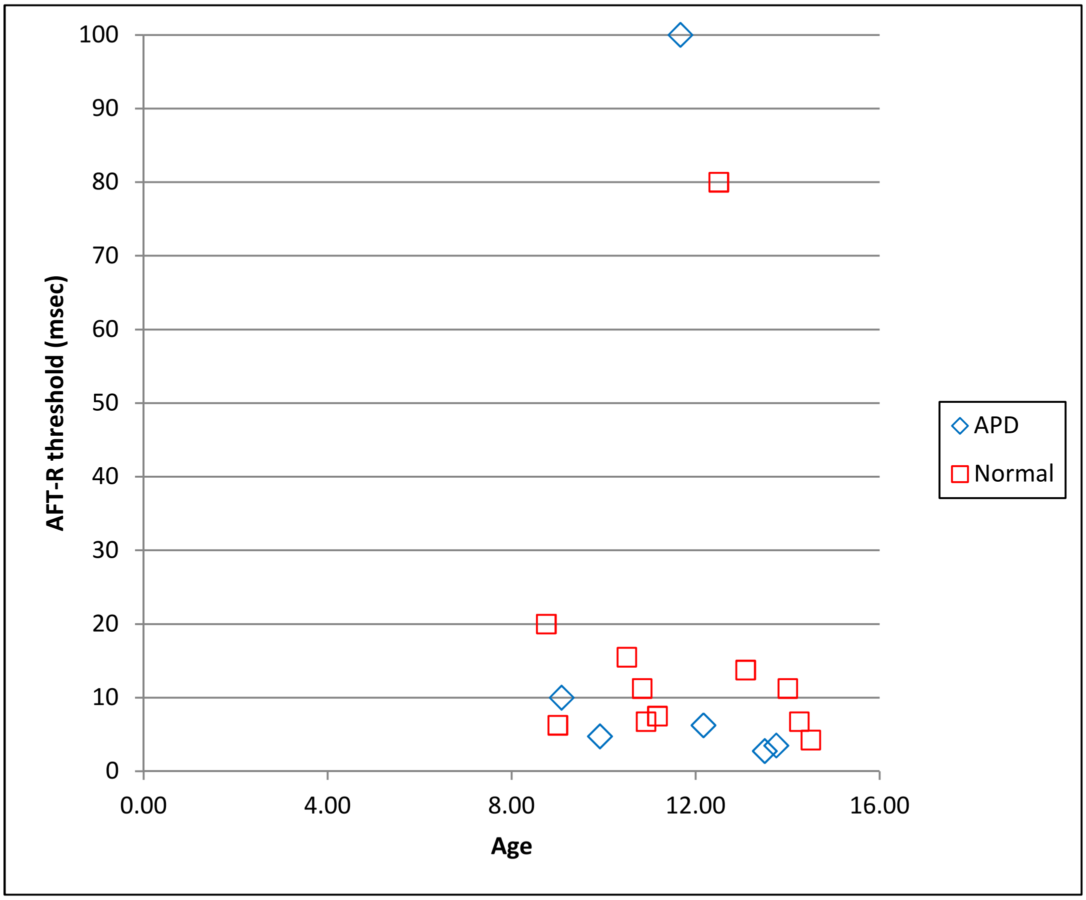


Figure 25 Average AFT-R fusion thresholds are shown as a function of age. The children identified with an auditory processing disorder are represented with the open blue diamonds. Typically developing children are represented by the open red squares.

Without including any break time that may have occurred between the tests, the estimated total test time for the completion of two AFT-R tests was slightly over 4 minutes and the range of completion times for the two adaptive 3AFC gap detection tasks fell between 9 and 10 minutes. The difference was attributable to test methodology and format. The AFT-R presents tone pairs to the listener with a set inter-stimulus interval for response purposes. The adaptive 3AFC gap detection task presents three signals in each trial and uses computer generated animated graphics. Additional standard signal presentations in combination with the graphic animations (enter and exit screen and provision of feedback) lengthen the overall test time. The other source of longer test time is the unregulated listener response time window in the adaptive 3AFC gap detection task. For each trial, the computer waits for the listener response following the presentation of test stimuli. Because there was no limit to the allowed response time this served to increase the overall test time.

Figure 26 shows the data for all participants who completed two blocks in each condition (adaptive 3AFC gap detection and AFT-R). The data have been plotted on a logarithmic scale. In Figure 26 the APD group is represented by the open blue diamonds and the typically developing group by the open red squares. A paired t-test demonstrated that here was no significant difference found between the average psychoacoustic gap detection and average AFT-R threshold, $t(16) = 1.472$, $p = 0.160$. There was no significant difference found between the thresholds achieved by the two groups (APD & typically developing) on either measure Pillai's Trace = 0.033, $F(1,14) = 0.239$, $p = 0.790$, $\eta^2 = 0.033$. The five children unable to achieve an AFT-R threshold after three attempts had no difficulty successfully achieving gap detection thresholds on the adaptive 3AFC task. An additional two children demonstrated age appropriate gap detection thresholds with the adaptive 3AFC task but had AFT-R thresholds that were elevated. Interpretation of temporal resolution abilities would differ significantly depending on the test employed with these two children. For a total of seven children, a comparison of the AFT-R and adaptive 3AFC gap detection thresholds suggest that the ability to detect the gap imbedded in a signal was not difficult but that the AFT-R test procedure itself was likely problematic and led to the poor performance on that test.

Problems with the test procedure may have resulted from individual differences in abilities such as maintaining attention on the task and/or an understanding of the test instructions/expectations.

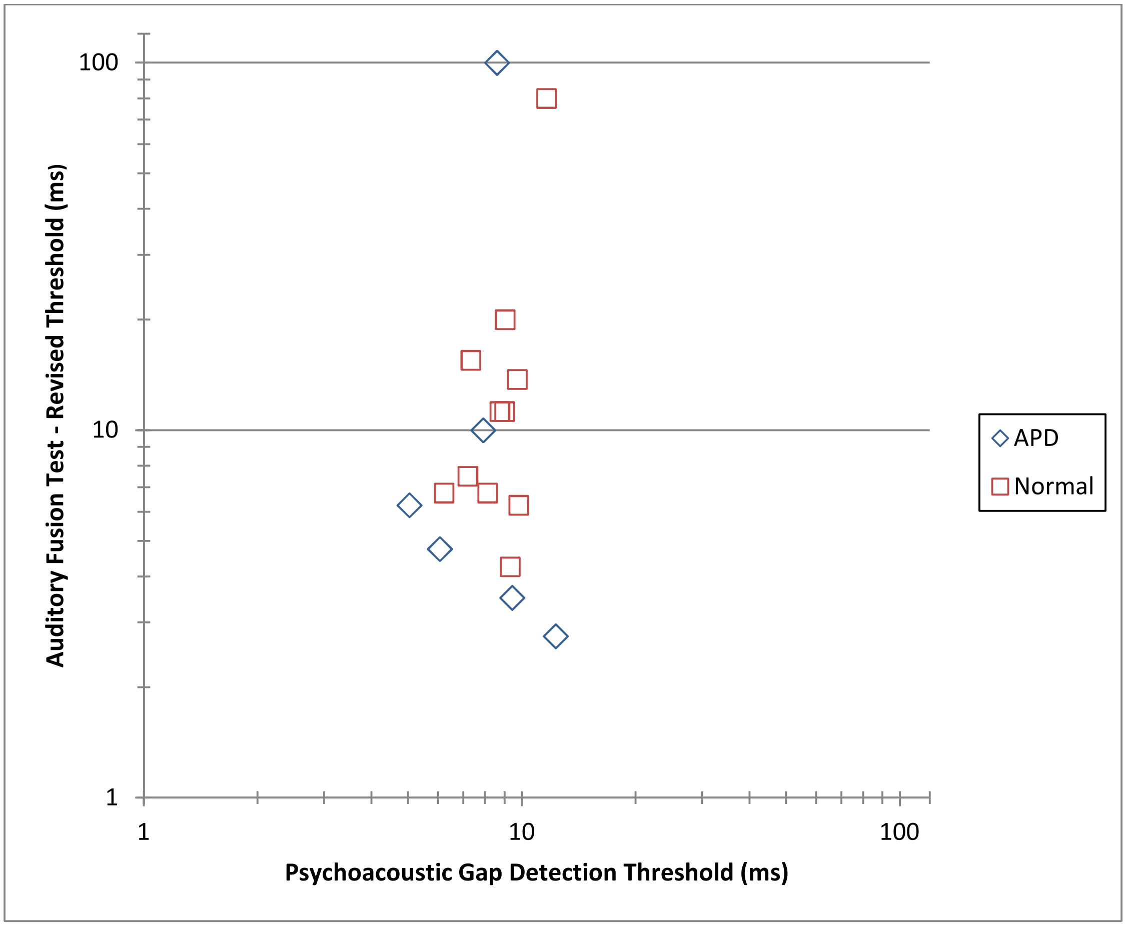


Figure 26 AFT-R fusion threshold is shown as a function of the gap detection threshold. Children with APD are represented with open blue diamonds and typically developing children are represented by the open red squares.

8.6.3 Discussion

The purpose of this study was to investigate the performance of children with and without an auditory processing disorder on a measure of gap detection thresholds using two methodologies, one a pre-recorded test used in typical clinical settings and the other, a more experimental task that uses an adaptive 3AFC procedure. The intent of the study was to evaluate the extent to which the methods produce similar results in terms of threshold estimates, reliability and clinical efficacy. The measures used in this study included the Auditory Fusion Test – Revised (McCroskey & Keith, 1996), a commercially available clinical test, and a psychoacoustic adaptive 3AFC gap detection task developed in the Child Hearing Research Lab at the National Centre for Audiology. A significant statistical difference was not observed between the thresholds estimated on the Auditory Fusion Test – Revised and the psychoacoustic adaptive 3AFC gap detection task. Results of the study also revealed no statistically significant difference between the normal and APD group thresholds on the AFT-R or the psychoacoustic gap detection task. Although there was no statistically significant difference between the scores obtained on these measures, the individual data suggests that the psychoacoustic 3AFC gap detection task may have some advantages over the AFT-R.

Mean thresholds for the two methods were similar but the amount of variability seen in the test score standard deviation was greater for the AFT-R test. The psychoacoustic adaptive 3AFC gap detection task thresholds had a standard deviation of approximately 2 ms compared to the approximately 27 ms recorded for the AFT-R thresholds. This discrepancy of approximately 25 ms reflects a greater amount of variability in the AFT-R thresholds than in those recorded for the adaptive gap detection task. Contributing to the increased variability of the AFT-R thresholds were two listeners that demonstrated normal psychoacoustic adaptive 3AFC gap detection thresholds but had elevated AFT-R thresholds. Some variability is expected in a group of test scores but if variability is too great it becomes difficult to use the measure as a reliable test. As variability in thresholds for any measurement increases the range of normally expected test scores would expand and potentially increase the likelihood of a false negative/positive diagnosis. The lesser amount of variability in the thresholds recorded for the psychoacoustic adaptive 3AFC gap detection task may be considered an advantage in its development and use as a clinical assessment tool because the small range of expected variability better defines normal performance and therefore substantially reduces the number of children erroneously diagnosed as disordered.

Five children were unable to achieve AFT-R thresholds. These results suggested an inability to detect brief temporal gaps in signals and could have been interpreted as very poor temporal resolution abilities but the age appropriate adaptive 3AFC gap detection thresholds achieved by the same children disproved this contention. These five children are of particular interest because although they were excluded from the data analysis due to the inability to successfully complete the AFT-R test they were able to achieve age appropriate psychoacoustic gap detection thresholds with the adaptive 3AFC task. There may be advantages to the clinical use of the adaptive 3AFC gap detection task developed in the Child Hearing Research Laboratory that can be gleaned through an examination of the performance of listeners that had difficulty with the AFT-R test even if benefits are not evidenced in statistically significant threshold differences. The first advantage of the adaptive 3AFC gap detection task includes those features that encouraged attention to the listening task. Vigilance during test completion was promoted through the use of interesting graphics that guided the child through each trial, provided feedback for each response and marked progression through the trial block. These graphics are colourful and appealing to children and the format gave a game-like atmosphere to the listening task. The performance feedback further promoted attention to the task as the children developed a desire to select the "different" sound in order to see the animation of the computer graphics that occurred as a result of the correct identification of the target stimulus. During the block of trials a graphic traveled across the bottom of the screen, tracking the test progression. This particular graphic appeared to reduce or satiate the need for children to know how much longer the test would take and promoted attention to completing the task. The option of different graphics for each block of trials kept the children interested and willing to engage in completing the task.

Another advantage of the adaptive gap detection task was the oddity format. The three interval forced choice oddity paradigm provided the children with two standard signals along with the target signal (included a temporal gap) during each trial. The presence of the comparative signals on each trial would have reduced the memory demands of the task and potentially improved thresholds. The advantage of the three interval forced choice was demonstrated by Schlauch and Rose in 1990 when they used Monte Carlo and behavioural testing to compare performance on a two, three and four interval forced choice. The authors concluded that the three interval forced choice afforded a significant advantage over the two interval but that increasing to four intervals did not substantially increase performance and that listeners my actually have been more susceptible to memory lapses. The instructions for the oddity paradigm are easily understood and constitute another advantage. The listeners were instructed to select and touch the graphic that sounded different. The meaning of this instruction was clear - to identify a just noticeable difference between the target and standard stimuli. This is an instruction that even very young children can understand and it does not require further explanation of the acoustic feature for which the listener must attend. Because the listener receives no coaching regarding the acoustic feature they are to identify, the instruction is general enough to use for a variety of different signals and tasks. This simple instruction for the listening task reduces or even eliminates any confounds that could occur as a result of a speech-language delay not only because it is easily understood but also because there are no demands for verbal responses.

Test time for the psychoacoustic adaptive 3AFC gap detection task was longer than for the AFT-R. Test time for the AFT-R was recorded as less than 5 minutes. Test time for the adaptive gap detection task ranged between 8 and 10 minutes. The AFT-R, as a pre-recorded test, had a response time allotment that was rigidly set so there was little variation in test time. The psychoacoustic adaptive 3AFC task did take longer to complete than the AFT-R due to the time required for graphic entry, exit and animation as well as listener response time. The psychoacoustic task inter-trial interval was not fixed but varied such that a new trial was not introduced to the listener until a response was received for the signals that had already been presented. This allowed the listener the opportunity to register their response at their own individual pace. Typically, children would respond quickly to targets that included a relatively large gap size but took more time to consider those trials that had target signals with a small gap. This flexibility for response time may have improved attention to the signal by keeping the test moving at a pace that was somewhat determined by the listener.

Despite the additional test time, likely introduced by the use of graphics in the psychoacoustic procedure, there appear to be some benefits afforded by the psychoacoustic adaptive 3AFC task. In this study there were two children that had significantly elevated thresholds on the AFT-R task but demonstrated gap detection thresholds within the normal range on the adaptive 3AFC task. These two individuals may have misunderstood the instructions for the AFT-R task or may have set their internal gap detection criteria at an extreme. There were an additional 5 children that, even with 3 attempts, were unable to achieve a threshold on the AFT-R task but could achieve a gap detection threshold within expected range using the adaptive 3AFC task. This finding suggests that the false positive identification of children with temporal resolution deficits is higher for the clinical measure in comparison to the psychoacoustic test. Several factors may contribute to this reduction in false positive finding, one being the adaptive procedure that allows for multiple runs. The adaptive procedure brackets the listener's threshold and by doing this affords a balance of easily identified targets and discrimination challenges. The use of graphics may assist in two ways. First, the visual stimulation assists in maintaining the listener's attention to the task and the graphics employed in this task also continuously provide children with information regarding their proximity to the end of the trial block. The second way the graphics may assist in reducing false positive outcomes is by way of the trial by trial feedback that provides the listener with information regarding their performance. The alternative and standard signal comparison may also be an advantage for children because it reduces memory and cognitive load and encourages an appropriate criterion setting.

The game-like format along with the use of colourful graphics and positive reinforcement appears to be a significant advantage for the assessment of auditory processing skills in children. The signals were generated in real time and the target was adapted in a way that quickly narrowed the search for the listener's threshold. This allowed for several ascending and descending runs of trials but kept the task interesting as there were rarely lengthy periods of time when all responses were either correct or incorrect. This resulted in regular exposure to the correct response graphics and acted as positive reinforcement toward the continued attention to the stimuli and task.

Similar to those tests employed in the clinical assessment of auditory processing abilities, it was evident that the ability to encode acoustic signal features is not a universal problem for the clinical population. The significance of this finding is that those children with signal encoding problems may benefit from treatment programs that would differ from those children that do not demonstrate these challenges and equally important is the revelation that some children with auditory skill deficits could go undiagnosed if signal encoding abilities are not assessed.

8.7 Future Directions

Given the findings of this initial research project into the signal encoding abilities of children suspected of having an auditory processing deficit it appears clear that there is a need to conduct further investigation into this area. Future research can take a number of different directions. However, a priority should be given to the translation of signal encoding evaluation from the laboratory into the clinical setting so that this void in auditory skill assessment can be eliminated. Preliminary results of the comparative study included in this project suggest that the adaptive forced-choice psychoacoustic procedure has potential for use in the clinical setting. The identification of those signal encoding abilities that may be the most sensitive for diagnostic purposes is essential. Larger samples of children completing a number of signal encoding tasks will be necessary to gain insight into the signal features that may identify the most children with poor encoding abilities. Clinicians have a limited amount of time for the assessment of children that display listening difficulties so it is important to identify a few signal encoding tasks that will provide the least number of false negative results and yet keep false positive outcomes to a minimum. The development of a screening tool may be advantageous for the purpose of identifying those children that require further investigation of their signal encoding abilities.

The adaptive forced choice method appears to have many benefits and the potential to be an effective tool not only for the assessment of signal encoding abilities but also to discriminate between children with auditory skill deficits and those with attention deficits. Further research into the qualitative evaluation of the trial-by-trial responses of children may yield insight into the nature of the disorder as well as solidify progress towards a means to tease-apart the APD and inattentive populations.

Once the clinical protocol for the assessment of signal encoding abilities has been established work towards remediation can commence. There is evidence that direct treatment for poor signal encoding abilities can be successful (Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Russo, Nicol, Zecker, Hayes, & Kraus, 2005) but further work in this area is required so that treatment goals and outcome measures will be available for clinicians.

8.8 Final Comments

Children with and without an auditory processing disorder, diagnosed with a typical clinical test battery, can have poor acoustic signal feature encoding. For those children that are genuinely poor performers and demonstrate difficulty with signal feature encoding, the classroom environment is very challenging. It is the combination of a degraded listening condition, including elevated noise levels, with the need to learn new and unfamiliar information that makes the environment challenging. In order to understand instructions and learn new information the students depend on the encoding of signal features. This reliance on efficient and accurate signal feature encoding occurs because cognition depends more heavily on bottom-up processing in the event of unfavourable listening conditions. The higher cognitive centres depend on the accuracy of the encoded signal to make sense of information that is heard in less than ideal conditions. When encoding is accurate and efficient the listener is able to understand information they hear, follow instructions easily and can accurately assimilate new information. Learning is not interrupted. When signal encoding is inefficient the student can become confused about activities and instructions. They later discover that information they heard was inaccurate and was misrepresented or assimilated in an erroneous fashion. The ability to hear and encode the signals provides the necessary and essential information for higher levels of processing. If children have been identified as having an APD then the intervention strategies put in place for them will assist in improving the opportunity for accurate signal encoding. For those children that have poor signal encoding but are not identified as APD (as determined by the typical clinical test battery), their auditory processing disorder remains undiagnosed and these children do not receive the intervention they require for success in the classroom setting.

There is a need to make efficient and user-friendly signal feature encoding tests available to clinicians for use in assessment of auditory processing abilities. A comparison of two gap detection tasks in this project resulted in the key finding that there was the lack of a statistically significant difference between the children's performance on the clinically available test of temporal resolution and the psychoacoustic adaptive 3AFC gap detection test developed in the laboratory. This result demonstrates that the laboratory test is at least as efficient as the clinically available test for the measurement of temporal resolution. This is evidence that the adaptive 3AFC psychoacoustic task is a tool that not only can be used in the evaluation of signal encoding abilities but that it can be employed as a reliable measurement tool for the investigation into these abilities in the clinical population suspected of having an auditory processing deficit. An additional advantage of the adaptive forced choice procedure is the ability to evaluate the trial-by-trial data to ascertain the reason or cause for the poor performance because this will have important ramifications in regards to diagnosis and intervention programs.

This project has demonstrated that signal encoding can be inefficient in children that demonstrate listening difficulties and are experiencing academic failure. It was also shown that the adaptive forced choice format can be effective in assessing signal encoding abilities in the clinical population. From this point continued effort should be made to further develop this tool for translation into the clinical setting for use in the assessment of auditory processing abilities in children.

References

Allen, P. & Allan, C. (2007). Auditory processing disorders: Putting the "neural" back into sensorineural hearing loss. In R.C. Seewald & J.M. Bamford (Eds.), *A Sound Foundation Through Early Amplification 2007: Proceedings of the Fourth International Conference* (pp. 221-233). Stäfa, Switzerland: Phonak AG.

Allen, P. & Wightman, F. (1992). Spectral pattern discrimination by children. *Journal of Speech and Hearing Research, 35*, 222-233.

Allen, P. & Wightman, F. (1994). Psychometric functions for children's detection of tones in noise. *Journal of Speech and Hearing Research, 37*, 205-215.

Allen, P., Wightman, F., Kistler, D. & Dolan, T. (1989). Frequency resolution in children. *Journal of Speech and Hearing Research, 35*, 222-233.

American Academy of Audiology. (2010). *Guidelines for the diagnosis, treatment and management of children and adults with central auditory processing disorder* [Clinical Practice Guidelines], Retrieved from http://www.audiology.org/resources/documentlibrary/Pages/CentralAuditoryProcessingDisorder.aspx.

American Speech-Language-Hearing Association. (1988). *Tympanometry* [Relevant Paper]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.RP1988-00027

American Speech-Language-Hearing Association. (1996). *Central auditory processing: Current status of research and implications for clinical practice* [Technical Report]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.TR1996-00241

American Speech-Language-Hearing Association. (1997). *Guidelines for audiologic screening* [Guidelines]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.GL1997-00199

American Speech-Language-Hearing Association. (2005a). *(Central) auditory processing disorders* [Technical Report]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.TR2005-00043

American Speech-Language-Hearing Association. (2005b). *Guidelines for manual pure-tone threshold audiometry* [Guidelines]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.GL2005-00014

American Speech-Language-Hearing Association. (2006). *Preferred practice patterns for the profession of audiology* [Preferred Practice Patterns]. Retrieved from ASHA website: htpp://www.asha.org/policy. doi:10.1044/policy.PP2006-00274

Amitay, S., Ahissar, M., & Nelken, I. (2002). Auditory processing deficits in reading disabled adults. *Journal of the Association for Research in Otolaryngology, 3*, 302-320. doi:10.1007/s101620010093

Anderson, S., Skoe, E., Chandrasekaran, B., Zecker, S., & Kraus, N. (2010). Brainstem correlates of speech-in-noise perception in children. *Hearing Research, 270*, 151-157. doi:10.1016/j.heares.2010.08.001

Attoni, T.M., & Mota, H.B. (2010). Study and analysis of contralateral acoustic reflex in children with phonological disorder. *Brazilian Journal of Otorhinolaryngology, 76*, 231-237.

Attoni, T.M., Quintas, V.G., & Mota, H.B. (2010). Auditory processing, acoustic reflex and phonological expression. *Brazilian Journal of Otorhinolaryngology, 76*, 753-761.

Bacon, S.P. & Viemeister, N.F. (1985). Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners. *Audiology, 24*, 117-134.

Bacon, S.P. & Viemeister, N.F. (1994). Intensity discrimination and increment detection at 16 kHz. *Journal of the Acoustical Society of America, 95*, 2616-2621.

Badri, R., Siegel, J.H., & Wright, B.A. (2011). Auditory filter shapes and high-frequency hearing in adults who have impaired speech in noise performance despite clinically normal audiograms. *Journal of the Acoustical Society of America, 129*, 852-863. doi:10.1121/1.3523476

Bailey, P.J. & Snowling, M.J. (2002). Auditory processing and the development of language and literacy. *British Medical Bulletin, 63*, 135-146.

Bamiou, D.E. & Luxon, L.M. (2008). Auditory processing disorders. *British Medical Journal, 337*:a2080. doi: 10.1136/bmj.a2080

Bamiou, D.E., Musiek, F.E. & Luxon, L.M. (2001). Aetiology and clinical presentations of auditory processing disorders – a review. *Archives of Disease in Childhood, 85*, 361-365.

Banai, K. & Ahissar, M. (2006). Auditory processing deficits in dyslexia: Task or stimulus related? *Cerebral Cortex, 16*, 1718-1728. doi:10.1093/cercor/bhj107

Barry, S.J. & Larson, V.D. (1974). Brief-tone audiometry with normal and deaf school-age children. *Journal of Speech and Hearing Disorders, 39*, 457-464.

Basu, M., Krishnan, A., & Weber-Fox, C. (2010). Brainstem correlates of temporal auditory processing in children with specific language impairment. *Developmental Science, 13*, 77-91. doi:10.1111/j.1467-7687.2009.00849.x

Bellis, T.J. (2006). Audiologic behavioral assessment of APD. In T.K. Parthasarathy (Ed.), *An Introduction to Auditory Processing Disorders in Children* (pp. 63-80). New York, NY: Lawrence Erlbaum Associates, Incorporated.

Bench, J. (1998). Central auditory processing disorder. In J. Doyle (Ed.), *Practical Audiology for Speech-Language Therapists* (pp. 213-247). London, United Kingdom: Whurr Publishers Limited.

Berg, K.M. & Boswell, A.E. (2000). Noise increment detection in children 1 to 3 years. *Perception & Psychophysics, 62*, 868-873.

Bishop, D.M.V. & McArthur, G.M. (2005). Individual differences in auditory processing in specific language impairment: A follow-up study using event-related potentials and behavioural thresholds. *Cortex, 41*, 327-341.

Boets, B., Wouters, J., van Wieringen, A., & Ghesquiere, P. (2007). Auditory processing, speech perception and phonological ability in pre-school children at high-risk for dyslexia: A longitudinal study of the auditory temporal processing theory. *Neuropsychologia, 45*, 1608-1620. doi:10.1016/j.neuropsychologia.2007.01.009

Bradley, J.S. (2005). Does the classroom assist or impede the learning process? *Canadian Association of Principals Journal, 13*, 32-34.

Bull, D., Schneider, B.A., & Trehub, S.E. (1981). The masking of octave-band noise by broad-spectrum noise: A comparison of infant and adult thresholds. *Perception and Psychophysics, 30*, 101-106.

Buunen, T.J.F. & van Valkenburg, D.A. (1979). Auditory detection of a single gap in noise. *Journal of the Acoustical Society of America, 65*, 534-537.

Buus, S., Florentine, M., & Redden, R.B. (1982). The SISI test: A review. *Audiology, 21*, 273-293.

Carlyon, R.P., & Moore, B.C.J. (1984). Intensity discrimination: A severe departure from Weber's law. *Journal of the Acoustical Society of America, 76*, 1369-1376

Carneol, S.O. (2008). Elusive, inclusive, or conclusive? (Central) auditory processing disorder. In J.N. Apps, R.F. Newby, & R.W. Roberts (Eds.), *Pediatric Neuropsychology Case Studies: From the Exceptional to the Commonplace*. Springer Science + Business Media, LLC. doi:10.1007/978-0-387-78965-1_29

Carrow-Woolfolk, E. (1996). *Oral and Written Language Scales*. San Antonio, TX: Pearson Education Incorporated.

Cestnick, L., & Jerger, J. (2000). Auditory temporal processing and lexical/nonlexical reading in developmental dyslexics. *Journal of the American Academy of Audiology, 11*, 501-513.

Chermak, G.D. (2002). Deciphering auditory processing disorders in children. *Otolaryngologic Clinics of North America, 35*, 733-749.

Chermak, G.D., Hall, J.W., & Musiek, F.E. (1999). Differential diagnosis and management of central auditory processing disorder and attention deficit hyperactivity disorder. *Journal of the American Academy of Audiology, 10*, 289-303.

Chermak, G.D. & Lee, J. (2005). Comparison of children's performance on four tests of temporal resolution. *Journal of the American Academy of Audiology, 16*, 554-563.

Chermak, G.D. & Musiek, F.E. (1997). Considerations in the assessment of central auditory processing disorders. In *Central Auditory Processing Disorders – New Perspectives* (pp. 91-107). San Diego, CA: Singular Publishing Group, Incorporated.

Chermak, G.D., Somers, E.K. & Seikel, J.A. (1998). Behavioral signs of central auditory processing disorder and attention deficit hyperactivity disorder. *Journal of the American Academy of Audiology, 9*, 78-84.

Chermak, G.D., Tucker, E., & Seikel, J.A. (2002). Behavioral characteristics of auditory processing disorder and attention-deficit hyperactivity disorder: Predominantly inattentive type. *Journal of the American Academy of Audiology, 13*, 332-338.

Clock, A.E., Salvi, R.J., Saunders, S.S., & Powers, N.L. (1993). Neural correlates of temporal integration in the cochlear nucleus of the chinchilla. *Hearing Research, 71*, 37-50.

Clock-Eddins, A., Salvi, R.J., Wang, J., & Powers, N.L. (1998). Threshold-duration functions of chinchilla auditory nerve fibers. *Hearing Research, 119*, 135-141.

Cole, R.A. & Jakimik, J. (1980). How are syllables used to recognize words? *Journal of the Acoustical Society of America, 67*, 965-970.

Cook, J.R., Mausbach, T., Burd, L., Gascon, G.G., Slotnick, H.B., Patterson, B., Johnson, R.D., Hankey, B., & Reynolds, B.W. (1993). A preliminary study of the relationship between central auditory processing disorder and attention deficit disorder. *Journal of Psychiatry and Neuroscience, 18*, 130-137.

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

Dawes, P. & Bishop, D. (2009). Auditory processing disorder in relation to developmental disorders of language, communication and attention: A review and critique. *International Journal of Language and Communication Disorders, 44*, 440-465. doi:10.1080/13682820902929073

Dawes, P. & Bishop, D.V.M. (2010). Psychometric profile of children with auditory processing disorder and children with dyslexia. *Archives of Disease in Childhood, 95*, 432-436. doi: 101136/adc.2009.170118

Dawes, P., Bishop, D.V.M., Sirimanna, T. & Bamiou, D.E. (2008). Profile and aetiology of children diagnosed with auditory processing disorder (APD). *International Journal of Pediatric Otorhinolaryngology, 72*, 483-489. doi:10.1016/j.ijporl.2007.12.007

Dunn, L.M. & Dunn, L.M. (1997). *Peabody Picture Vocabulary Test, 3rd Edition*. Circle Pines, MN: American Guidance Service, Incorporated.

Emanuel, D.C., Ficca, K.N., & Korczak, P. (2011). Survey of the diagnosis and management of auditory processing disorder. *American Journal of Audiology, 20*, 48-60. doi:10.1044/1059-0889(2011/10-0019)

Fernell, E., Norrelgen, F., Bozkurt, I., Hellberg, G., & Lowing, K. (2002). Developmental profiles and auditory perception in 25 children attending special preschools for language-impaired children. *Acta Paediatrica, 91*, 1108-1115.

Fischer, B. & Hartnegg, K. (2004). On the development of low-level auditory discrimination and deficits in dyslexia. *Dyslexia, 10*, 105-118. doi:10.1002/dys.268

Fitzgibbons, P.J. & Wightman, F.L. (1982). Gap detection in normal and hearing-impaired listeners. *Journal of the Acoustical Society of America, 72*, 761-765.

Fitzpatrick, E.M. & Durieux-Smith, A. (2011). Universal newborn hearing screening improves quality of life in children aged 3-5years but does not show a clear relationship with spoken language skills. *Evidence-Based Medicine, 16*, 57-58.

Fletcher, H. (1940). Auditory patterns. *Reviews of Modern Physics, 12*, 47-65.

Florentine, M. (1986). Level discrimination of tones as a function of duration. *Journal of the Acoustical Society of America, 79*, 792-796.

Florentine, M., Buus, S., & Geng, W. (1999). Psychometric functions for gap detection in a yes-no procedure. *Journal of the Acoustical Society of America, 106*, 3512-3520.

Florentine, M., Buus, S., & Mason, C.R. (1987). Level discrimination as a function of level for tones from 0.25 to 16 kHz. *Journal of the Acoustical Society of America, 81*, 1528-1541.

France, S.J., Rosner, B.S., Hansen, P.C., Calvin, C., Talcott, J.B., Richardson, A.J., & Stein, J.F. (2002). Auditory frequency discrimination in adult developmental dyslexics. *Perception and Psychophysics, 64*, 169-179.

Freyman, R.L. & Nelson, D.A. (1991). Frequency discrimination as a function of signal frequency and level in normal-hearing and hearing-impaired listeners. *Journal of Speech and Hearing Research, 34*, 1371-1386.

Friel-Patti, S. (1999). Clinical decision-making in the assessment and intervention of central auditory processing disorders. *Language, Speech and Hearing Services in Schools, 30*, 345-352.

Garner, W.R. (1947a). Auditory thresholds of short tones as a function of repetition rates. *Journal of the Acoustical Society of America, 19*, 600-608.

Garner, W.R. (1947b). The effect of frequency spectrum on temporal integration of energy in the ear. *Journal of the Acoustical Society of America, 19*, 808-815.

Garner, W.R., & Miller, G.A. (1947). The masked threshold of pure tones as a function of duration. *Journal of Experimental Psychology, 37*, 293-303.

Gengle, R.W., & Watson, C.S. (1971). Temporal Integration: I. Clinical implications of a laboratory study. II. Additional data from hearing-impaired subjects. *Journal of Speech and Hearing Disorders, 36*, 213-224.

Gerken, G.M., Bhat, V.K.H., & Hutchinson-Clutter, M. (1990). Auditory temporal integration and the power function model. *Journal of the Acoustical Society of America, 88*, 767-778.

Gerken, G.M., Gunnarson, A.D., & Allen, C.M. (1983). Three models of temporal summation evaluated using normal-hearing and hearing-impaired subjects. *Journal of Speech and Hearing Research, 26*, 256-262.

Goldman, R., Fristoe, M., & Woodcock, R.W. (1970). *Goldman-Fristoe-Woodcock Test of Auditory Discrimination*. San Antonio, TX: Pearson Education Incorporated.

Goldstein, R. & Kramer, J.C. (1960). Factors affecting thresholds for short tones. *Journal of Speech and Hearing Research, 3*, 249-256.

Goldstone, R.L. (1998). Perceptual learning. *Annual Review of Psychology, 49*, 585-612.

Goldstone, R.L. (2003). Learning to perceive while perceiving to learn. In R. Kimchi, M. Behrmann & C. Olson (Eds.) *Perceptual Organization in Vision: Behavioral and Neural Perspectives* (pp. 233-278). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Gomez, R. & Condon, M. (1999). Central auditory processing ability in children with ADHD with and without learning disabilities. *Journal of Learning Disabilities, 32*, 150-158.

Goncalves, I.C., Wertzner, H.F., Samelli, A.G., & Matas, C.G. (2011). Speech and non-speech processing in children with phonological disorders: an electrophysiological study. *Clinics, 66*, 293-298. doi:10.1590/S1807-59322011000200019

Gopal, K.V., Daily, C.S., & Kao, K. (2002). Auditory brainstem responses to regular and high stimulus repetition rates in children at risk for central auditory processing disorders. *Journal of Audiological Medicine, 11*, 146-160.

Gopal, K.V. & Kowalski, J. (1999). Slope analysis of auditory brainstem responses in children at risk of central auditory processing disorders. *Scandinavian Audiology, 28*, 85-90.

Gordon-Salant, S. & Fitzgibbons, P. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech and Hearing Research, 36*, 1276-1285.

Green, D.M. (1973). Temporal acuity as a function of frequency. *Journal of the Acoustical Society of America, 54*, 373-379.

Green, D.M., Birdsall, T.G., & Tanner, W.P. (1957). Signal detection as a function of signal intensity and duration. *Journal of the Acoustical Society of America, 29*, 523-531.

Greenberg, G.Z. & Larkin, W.D. (1968). Frequency-response characteristic of auditory observers detecting signals of a single frequency in noise: The probe-signal method. *Journal of the Acoustical Society of America, 44*, 1513-1523.

Hall, J.W. & Fernandes, M.A. (1983). Temporal integration, frequency resolution, and off-frequency listening in normal-hearing and cochlear-impaired listeners. *Journal of the Acoustical Society of America, 74*, 1172-1177.

Hall, J.W. & Grose, J.H. (1991). Notched-noise measures of frequency selectivity in adults and children using fixed-masker-level and fixed-signal-level presentation. *Journal of Speech and Hearing Research, 34*, 651-660.

Halliday, L.F. & Bishop, D.V.M. (2006). Auditory frequency discrimination in children with dyslexia. *Journal of Research in Reading, 29*, 213-228.

Halliday, L.F., Taylor, J.L., Edmondson-Jones, A.M., & Moore, D.R. (2008). Frequency discrimination learning in children. *Journal of the Acoustical Society of America, 123*, 4393-4402.

Harbert, F., Young, I.M., & Weiss, B.G. (1969). Clinical application of intensity difference limen. *Acta Oto-laryngologica, 67*, 435-443.

Hartley, D.E.H. & Moore, D.R. (2002). Auditory processing efficiency deficits in children with developmental language impairments. *Journal of the Acoustical Society of America, 112*, 2962-2966. doi:10.1121/1.1512701

Hautus, M.J., Setchell, G.J., Waldie, K.E., & Kirk, I.J. (2003). Age-related improvements in auditory temporal resolution in reading-impaired children. *Dyslexia, 9*, 37-45. doi:10.1002/dys.234

He, N., Dubno, J.R., & Mills, J.H. (1998). Frequency and intensity discrimination measured in a maximum-likelihood procedure from young and aged normal-hearing subjects. *Journal of the Acoustical Society of America, 103*, 553-565.

He, S., Buss, E., & Hall, J.W. (2010). Monaural temporal integration and temporally selective listening in children and adults. *Journal of the Acoustical Society of America, 127*, 3643-3653. doi:10.1121/1.3397464

Heiervang, E., Stevenson, J. & Hugdahl, K. (2002). Auditory processing in children with dyslexia. *Journal of Child Psychology and Psychiatry, 43*, 931-938.

Heil, P. & Neubauer, H. (2003). A unifying basis of auditory thresholds based on temporal summation. *Proceedings of the National Academy of Science of the United States of America, 100*, 6151-6156. doi:10.1073/pnas.1030017100

Heine, C. & Slone, M. (2008). The impact of mild central auditory processing disorder on school performance during adolescence. *Journal of School Health, 78*, 405-407.

Hickson, F. & Newton, V. (2000). Central auditory processing disorder (CAPD) in children: What is it and what are the issues surrounding it? *Deafness and Education International, 2*, 75-85.

Hill, P.R., Hartley, D.E.H., Glasberg, B.R., Moore, B.C.J., & Moore, D.R. (2004). Auditory processing efficiency and temporal resolution in children and adults. *Journal of Speech, Language, and Hearing Research, 47*, 1022-1030.

Hill, P.R., Hogben, J.H. & Bishop, D.M.V. (2005). Auditory frequency discrimination in children with specific language impairment: A longitudinal study. *Journal of Speech, Language, and Hearing Research, 48*, 1136-1146.

Hoglund, E.M. & Feth, L.L. (2009). Spectral and temporal integration of brief tones. *Journal of the Acoustical Society of America, 125*, 261-269. doi:10.1121/1.2999338

Holstrum, W.J., Biernath, K., McKay, S. & Ross, D.S. (2009). Mild and unilateral hearing loss: Implications for early intervention. *Infants & Young Children, 22*, 177-187.

Hood, L.J. (1998). *Clinical Applications of the Auditory Brainstem Response*. San Diego, CA: Singular Publishing Group, Incorporated.

Hornickel, J., Chandrasekaran, B., Zecker, S., & Kraus, N. (2011). Auditory brainstem measures predict reading and speech-in-noise perception in school-aged children. *Behavioural Brain Research, 216*, 597-605. doi:10.1016/j.bbr.2010.08.051

Howard, C.S., Munro, K.J. & Plack, C.J. (2010). Listening effort at signal-to-noise ratios that are typical of the school classroom. *International Journal of Audiology, 49*, 928-932. doi:10.3109/14992027.2010.520036

Hughes, J.W. (1946). The threshold of audition for short periods of stimulation. *Proceedings of the Royal Society of London: Series B, Biological Sciences, 133*, 486-493.

Hurley, R.M. & Fulton, S.E. (2007). Psychoacoustic considerations and implications for the diagnosis of (C)APD. In F.E. Musiek & G.D Chermak (Eds.), *Handbook of (Central) Auditory Processing Disorder: Vol. 1. Auditory Neuroscience and Diagnosis* (pp. 13-51). San Diego, CA: Plural Publishing Incorporated.

Hutchinson, K.M. & Mauer, D.M. (1998). Targeting academic success: An interdisciplinary assessment program for children with central auditory processing deficits. *Volta Review, 100*, 235-260.

Iliadou, V., Bamiou, D., Kaprinis, S., Kandylis, D. & Kaprinis, G. (2009). Auditory processing disorders in children suspected of learning disabilities – A need for screening? *International Journal of Pediatric Otorhinolaryngology, 73*, 1029-1034.

Ingram, J.G. (1970). Individual differences in signal detection. *Acta Psychologica, 34*, 39-50.

Irwin, R.J., Ball, A.K.R., Kay, N., Stillman, J.A. & Rosser, J. (1985). The development of auditory temporal acuity in children. *Child Development, 56*, 614-620.

Irwin, R.J., Stillman, J.A., & Schade, A. (1986). The width of the auditory filter in children. *Journal of Experimental Child Psychology, 41*, 429-442.

Ivey, R. (1969). *Words in Ipsilateral Competition (WIC)*, (Unpublished Masters Thesis), Colorado State University, Fort Collins, CO.

Ivey, R.G. (1987). [Words in ipsilateral competition (WIIC) – Version 2]. Unpublished Normative Study.

Ivey, R.G., & Willeford, J.A. (1988). Three tests of CNS auditory function. *Human Communication Canada, 12*, 35-43.

Jensen, J.K. & Neff, D.L. (1993). Development of basic auditory discrimination in preschool children. *Psychological Science, 4*, 104-107.

Jerger, S. (2007). Current state of knowledge: Perceptual processing by children with hearing impairment. *Ear and Hearing, 28*, 754-765.

Jesteadt, W., & Sims, S. (1975). Decision processes in frequency discrimination. *Journal of the Acoustical Society of America, 57*, 1161-1168.

Jesteadt, W., Wier, C.C., & Green, D.M. (1977). Intensity discrimination as a function of frequency and sensation level. *Journal of the Acoustical Society of America, 61*, 169-177.

Jirsa, R.E. (2001). Maximum length sequences-auditory brainstem responses from children with auditory processing disorders. *Journal of the American Academy of Audiology, 12*, 155-164.

Jutras, B. & Gagne, J.P. (1999). Auditory sequential organization among children with and without a hearing loss. *Journal of Speech, Language, and Hearing Research, 42*, 553-567.

Katz, J. (1998). *The Staggered Spondaic Word Test (SSW) Fifth Edition*, Vancouver, WA: Precision Acoustics.

Katz, J. & Wilde, L. (1994). Auditory processing disorders. In J. Katz (Ed.), *Handbook of Clinical Audiology* (4th ed., pp. 490-502). Baltimore, MD: Williams & Wilkins.

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

Keith, R.W. (2000a). *SCAN-C: Test for Auditory Processing Disorders in Children – Revised*. San Antonio, TX: The Psychological Corporation.

Keith, R.W. (2000b). *Random Gap Detection Test*. St. Louis, MO: AUDiTEC Inc.

Keith, R.W. (2004). Auditory Processing Disorders. In R.J. Roeser & M.P. Downs (Eds.), *Auditory Disorders in School Children* (4th ed., pp. 124-146). New York, NY: Thieme Medical Publishers Inc.

Keller, W.D. & Tillery, K.L. (2002). Reliable differential diagnosis and effective management of auditory processing and attention deficit hyperactivity disorders. *Seminars in Hearing, 23*, 337-347.

Kidd, G. (2002). Psychoacoustics. In J. Katz (Ed.), *Handbook of Clinical Audiology* (5th ed., pp. 33-49). Baltimore, MD: Lippincott Williams & Wilkins.

Klatte, M. & Hellbruck, J. (2010). Effects of classroom acoustics on performance and well-being in elementary school children: A field study. *Environment and Behavior, 42*, 659-692.

Koravand, A., Jutras, B., & Roumy, N. (2010). Peripheral hearing loss and auditory temporal ordering ability in children. *International Journal of Pediatric Otorhinolaryngology, 74*, 50-55.

Lasky, E.Z. (1983). Parameters Affecting Auditory Processing. In. E. Z. Lasky & J. Katz (Eds.), *Central Auditory Processing Disorders: Problems of Speech, Language, and Learning* (pp. 11-29). Austin, Tx: PRO-ED, Incorporated.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467-477.

Levy, S. & Parkin, C.M. (2003). Are we yet able to hear the signal through the noise? A comprehensive review of central auditory processing disorders: Issues of research and practice. *Canadian Journal of School Psychology, 18*, 153-182.

Lister, J.J., Roberts, R.A., Shackelford, J., & Rogers, C.L. (2006). An adaptive clinical test of temporal resolution. *American Journal of Audiology, 15*, 133-140.

Macmillan, N.A. & Creelman, C.D. (1990). Response bias: Characteristics of detection theory, threshold theory, and “nonparametric” indexes. *Psychological Bulletin, 107*, 401-413.

Martin, N.A. & Brownell, R. (2005). *Test of Auditory Processing Skills* (3rd ed.). Novato,CA: Academic Therapy Publications.

Maxon, A.B. & Hochberg, I. (1982). Development of psychoacoustic behavior: Sensitivity and discrimination. *Ear and Hearing, 3*, 301-308.

McArthur, G.M. & Bishop, D.V.M. (2004a). Which people with specific language impairment have auditory processing deficits? *Cognitive Neuropsychology, 21*, 79-94. doi:1080/02643290342000087

McArthur, G.M. & Bishop, D.V.M. (2004b). Frequency discrimination deficits in people with specific language impairment: Reliability, validity, and linguistic correlates. *Journal of Speech, Language, and Hearing Research, 47*, 527-541.

McArthur, G.M., Ellis, D., Atkinsion, C.M., & Coltheart, M. (2008). Auditory processing deficits in children with reading and language impairments: Can they (and should they) be treated? *Cognition, 107*, 946-977. doi:10.1016/j.cognition.2007.12.005

McCann, D.C., Worsfold, S., Law, C.M., Mullee, M., Petrou, S., Stevenson, J., Yuen, H.M. & Kennedy, C.R. (2009). Reading and communication skills after universal newborn screening for permanent childhood hearing impairment. *Archives of Disabilities in Childhood, 94*, 293-297. doi:10.1136/adc.2008.151217

McCroskey, R.L. & Keith, R.W. (1996). *Auditory Fusion Threshold Test-Revised.* St. Louis, MO: Auditec.

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

McFadden, M.A. (2006). *The receptive prosodic abilities of children with auditory processing disorders: A comparative study*. (Unpublished master's thesis), The University of Western Ontario, London, Ontario, Canada.

Medwetsky, L. (1994). Educational audiology. In J. Katz (Ed.), *Handbook of Clinical Audiology* (4th ed., pp. 503-520). Baltimore, MD: Williams & Wilkins.

Moav, R., Nevo, N., & Banai, K. (2009). Central auditory processing development in adolescents with and without learning disabilities. *Journal of Basic and Clinical Physiology and Pharmacology, 20*, 207-217.

Moeller, M.P. (2000). Early intervention and language development in children who are deaf and hard of hearing. *Pediatrics, 106*, e43-52. doi:10.1542/peds.106.3.e43

Moore, B.C.J. (1995). Frequency analysis and masking. In B.C.J. Moore (Ed.), *Hearing* (pp. 161-205). San Diego, CA: Academic Press.

Moore, B.C.J. (2004). The perception of loudness. In *An Introduction to the Psychology of Hearing*, 5th Edition (pp. 127-161). San Diego, CA: Elsevier Academic Press.

Moore, D.R. (2006). Auditory processing disorder (APD): Definition, diagnosis, neural basis, and intervention. *Audiological Medicine, 4*, 4-11. doi:10.1080/16513860600568573

Moore, D.R., Amitay, S., & Hawkey, D.J.C. (2003). Auditory perceptual learning. *Learning & Memory, 10*, 83-85.

Moore, D.R., Cowan, J.A., Riley, A., Edmondson-Jones, A.M., & Ferguson, M.A. (2011). Development of auditory processing in 6- to 11-yr-old children. *Ear and Hearing, 32*, 296-285.

Moore, D.R., Ferguson, M.A., Edmondson-Jones, A.M., Ratib, S. & Riley, A. (2010). Nature of auditory processing disorder in children. *Pediatrics, 126*, e382-e390. doi:10.1542/peds.2009-2826

Moore, D.R., Ferguson, M.A., Halliday, L.F., & Riley, A. (2008). Frequency discrimination in children: Perception, learning and attention. *Hearing Research, 238*, 147-154. doi:10.1016/j.heares.2007.11.013

Moore, D.R., Halliday, L.F., & Amitay, S. (2009). Use of auditory learning to manage listening problems in children. *Philosophical Transactions of The Royal Society Biological Sciences, 364*, 409-420. doi:10.1098/rstb.2008.0187

Moore, D.R., Hogan, S.C., Kacelnik, O., Parsons, C.H., Rose, M.M., & King, A.J. (2001). Auditory learning as a cause and treatment of central dysfunction. *Audiology & Neuro-Otology, 6*, 216-220.

Musiek, F., Baran, J., & Pinheiro, M. (1990). Duration pattern recognition in normal subjects and patients with cerebral and cochlear lesions. *Audiology, 29*, 304-313.

Musiek, F.E., Shinn, J.B., Jirsa, R., Bamiou, D.E., Baran, J.A. & Zaidan, E. (2005). GIN (Gaps-In-Noise) test performance in subjects with confirmed central auditory nervous system involvement. *Ear & Hearing, 26*, 608-618.

Neubauer, H. & Heil, P. (2004). Towards a unifying basis of auditory thresholds: The effects of hearing loss on temporal integration reconsidered. *Journal of the Association for Research in Otolaryngology, 5*, 436-458. doi:10.1007/s10162-004-5031-4

Nickisch, A. & Massinger, C. (2009). Auditory processing in children with specific language impairments: Are there deficits in frequency discrimination, temporal auditory processing or general auditory processing? *Folia Phoniatrica et Logopaedica, 61*, 323-328. doi:10.1159/000252848

Norrelgen, F., Lacerda, F., & Forssberg, H. (2002). Temporal resolution of auditory perception and verbal working memory in 15 children with language impairment. *Journal of Learning Disabilities, 35*, 539-545.

Olsen, C.C., & Buckles, K.M. (1979). The effect of age in brief-tone audiometry. *Journal of Auditory Research, 19*, 117-122.

Olsen, W.O., & Carhart, R. (1966). Integration of acoustic power at threshold by normal hearers. *Journal of the Acoustical Society of America, 40*, 591-599.

Olsen, W.O., Rose, D.E., & Noffsinger, D. (1974). Brief-tone audiometry with normal, cochlear, and eighth nerve tumor patients. *Archives of Otolaryngology, 99*, 185-189.

Olsho, L.W. (1985), Infant auditory perception: Tonal masking. *Infant Behavior and Development, 8*, 371-384.

Palmer, C.V. (1997). Hearing and listening in a typical classroom. *Language, Speech & Hearing Services in Schools, 28*, 213-218.

Patterson, R.D. (1976). Auditory filter shapes derived with noise stimuli. *Journal of the Acoustical Society of America, 59*, 640-654.

Pedersen, C.B., & Elberling, C. (1972). Temporal integration of acoustic energy in normal hearing persons. *Acta Otolaryngologica, 74*, 398-405.

Pinheiro, M. (1977). *Pitch Pattern Sequence Test*. Auditec of St. Louis.

Plack, C.J. & Carlyon, R.P. (1995). Loudness perception and intensity coding. In B.C.J. Moore (Ed.), *Hearing* (pp. 123-160). San Diego, CA: Academic Press.

Plomp, R., & Bouman, M.A. (1959). Relation between hearing threshold and duration for tone pulses. *Journal of the Acoustical Society of America, 31*, 749-758.

Purdy, S.C., Kelly, A.S., & Davies, M.G. (2002). Auditory brainstem response, middle latency response, and late cortical evoked potentials in children with learning disabilities. *Journal of the American Academy of Audiology, 13*, 367-382.

Reynolds, C.R., Voress, J.K., & Pearson, N.A. (2008). *Developmental Test of Auditory Perception*. Austin, TX: ProEd.

Riccio, C.A., Cohen, M.J., Garrison, T., & Smith, B. (2005). Auditory processing measures: Correlation with neurophysiological measures of attention, memory, and behavior. *Child Neuropsychology, 11*, 363-372. doi:10.1080/09297040490916956

Riccio, C.A., Hynd, G.W., Cohen, M.J., & Molt, L. (1996). The Staggered Spondaic Word test: Performance of children with attention-deficit hyperactivity disorder. *American Journal of Audiology, 5*, 55-62.

Ronken, D.A. (1970). Monaural detection of a phase difference between clicks. *Journal of the Acoustical Society of America, 47*, 1091-1099.

Rosen, S. (1999). Language disorders: A problem with auditory processing? *Current Biology, 9*, R698-R700.

Rosen, S. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything? *Journal of Phonetics, 31*, 509-527. doi:10.1016/S0095-4470(03)00046-9

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

Ross, D.S., Gaffney, M., Green, D., & Holstrum, W.J. (2008). Prevalence and Effects. *Seminars in Hearing, 29*, 141-148.

Russo, N.M., Nicol, T.G., Zecker, S.G., Hayes, E.A., & Kraus, N. (2005). Auditory training improves neural timing in the human brainstem. *Behavioural Brain Research, 156*, 95-103.

Sahli, S. (2009). Auditory processing disorder in children: Definition, assessment and management. *Journal of International Advanced Otology, 5*, 104-115.

Sanders, J.W., Josey, A.F, & Kemker, F.J. (1971). Brief-tone audiometry in patients with VIIIth nerve tumor. *Journal of Speech and Hearing Research, 14*, 172-178.

Scharf, B. (1970). Critical Bands. In J.V. Tobias (Ed.), *Foundations of Modern Auditory Theory* (pp. 159-202). New York, NY: Academic Press, Inc.

Schafer, T.H., Gales, R.S., Shewmaker, C.A., & Thompson, P.O. (1950). The frequency selectivity of the ear as determined by masking experiments. *Journal of the Acoustical Society of America, 22*, 490-496.

Schlauch, A.R. & Rose, R.M. (1990). Two-, three-, and four-alternative forced-choice procedures: Estimator bias and efficiency. *Journal of the Acoustical Society of America, 88*, 732-740.

Schneider, B.A., Morrongiello, B.A., & Trehub, S.E. (1990). Size of critical band in infants, children, and adults. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 642-652.

Schneider, B.A., Trehub, S.E., Morrongiello, B.A., & Thorpe, L.A. (1989). Developmental changes in masked thresholds. *Journal of the Acoustical Society of America, 86*, 1733-1742.

Schorn, K. & Zwicker, E. (1990). Frequency selectivity and temporal resolution in patients with various inner ear disorders. *Audiology, 29*, 8-20.

Schwartz, S. & Gurian, A. (2003). Central auditory processing disorder (CAPD). *School Nurse News, 20*, 16-18.

Sek, A. & Moore, B.C.J. (1995). Frequency discrimination as a function of frequency, measured in several ways. *Journal of the Acoustical Society of America, 97*, 2479-2486.

Shailer, M.J. & Moore, B.C.J. (1983). Gap detection as a function of frequency, bandwidth, and level. *Journal of the Acoustical Society of America, 74*, 467-473.

Sharma, M., Purdy, S.C., & Kelly, A.S. (2009). Comorbidity of auditory processing, language, and reading disorders. *Journal of Speech, Language, and Hearing Research, 52*, 706-722.

Sheeley, E.C. & Bilger, R.C. (1964). Temporal integrationas a function of frequency. *Journal of the Acoustical Society of America, 36*, 1850-1857.

Shemesh, R. (2008). Psychoacoustic tests for central auditory processing: Normative data. *Journal of Basic and Clinical Physiology and Pharmacology, 19*, 249-259.

Smoski, W.J., Brunt, M.A., & Tannahill, J.C. (1992). Listening characteristics of children with central auditory processing disorders. *Language, Speech, and Hearing Services in Schools, 23*, 145-152.

Stephens, S.D.G. (1973). Auditory temporal integration as a function of intensity. *Journal of Sound and Vibration, 30*, 109-126.

Swets, J.A. (1996). Accuracy and Response Bias in Survey Research. In *Signal Detection Theory and ROC Analysis in Psychology and Diagnostics* (pp. 249-268). Mahwah, NJ: Lawrence Erlbaum Associates, Incorporated.

Swets, J.A., Green, D.M., & Tanner, W.P. (1988). On the width of critical bands. J.A. Swets, *Signal Detection and Recognition by Human Observers* (pp. 471-482). Los Altos, CA: Peninsula Publishing.

Swets, J.A., Tanner, W.P., & Birdsall, T.G. (1988). Decision processes in perception. In J.A. Swets, *Signal Detection and Recognition by Human Observers* (pp. 3-57). Los Altos, CA: Peninsula Publishing.

Tallal, P. (1976). Rapid auditory processing in normal and disordered language development. *Journal of Speech and Hearing Research, 19*, 561-571.

Tallal, P., Merzenich, M.M., Miller, S., & Jenkins, W. (1998). Language learning impairments: Integrating basic science, technology, and remediation. *Experimental Brain Research, 123*, 210-219.

Tallal, P., Miller, S., & Fitch, R.H. (1993). Neurobiological basis of speech: A case for the preeminence of temporal processing. *Annals of the New York Academy of Sciences, 682*, 27-47.

Tallal, P. & Newcombe, F. (1978). Impairment of auditory perception and language comprehension in dysphasia. *Brain and Language, 5*, 13-24.

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

Thompson, N.C., Cranford, J.L., & Hoyer, E. (1999). Brief-tone frequency discrimination by children. *Journal of Speech, Language, and Hearing Research, 42*, 1061-1068.

Vanniasegaram, I., Cohen, M., & Rosen, S. (2004). Evaluation of selected auditory tests in school-age children suspected of auditory processing disorders. *Ear and Hearing, 25*, 586-597. doi:10.1097/01.aud.0000151575.58269.19

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

Verhaert, N., Willems, M., Van Kerschaver, E. & Desloovere, C. (2008). Impact of early hearing screening and treatment on language development and education level: Evaluation of 6 years of universal newborn hearing screening (ALGO) in

Flanders, Belgium. *International Journal of Pediatric Otorhinolaryngology, 72*, 599-608. doi:10.1016/j.ijporl.2008.01.012

Viemeister, N.F. & Plack, C.J. (1993). Time Analysis. In W.A Yost, Popper, A.N., & Fay, R.R. (Eds.), *Human Psychophysics* (pp. 116-154). New York: Springer-Verlag.

Viemeister, N.F. & Wakefield, G.H. (1991). Temporal integration and multiple looks. *Journal of the Acoustical Society of America, 90*, 858-865.

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

Walker, K.M.M., Brown, D.K., Scarff, C., Watson, C., Muir, P., & Phillips, D.P. (2011). Temporal processing performance, reading performance, and auditory processing disorder in learning-impaired children and controls. *Canadian Journal of Speech-Language Pathology and Audiology, 35*, 6-17.

Walker, K.M.M., Hall, S.E., Klein, R.M., & Phillips, D.P. (2006). Development of perceptual correlates of reading performance. *Brain Research, 1124*, 126-141. doi:10.1016/j.brainres.2006.09.080

Watson, C.S., & Gengel, R.W. (1969). Signal duration and signal frequency in relation to auditory sensitivity. *Journal of the Acoustical Society of America, 46*, 989-997.

Wechsler Abbreviated Scales of Intelligence, 3rd Edition (1999). San Antonio, TX: The Psychological Corporation.

Welsh, L.W., Welsh, J.J., & Healy, M.P. (1996). Learning disabilities and central auditory dysfunction. *The Annals of Otology, Rhinology & Laryngology, 105*, 117-122

Wepman, J.M. & Reynolds, W.M. (1987). *Wepman's Auditory Discrimination Test* (2nd ed.). Torrance, CA: Western Psychological Services.

Werner, L.A., Marean, G.C., Halpin, C.F., Spetner, N.B., & Gillenwater, J.M. (1992). Infant auditory temporal acuity: Gap detection. *Child Development, 63*, 260-272.

Wible, B., Nicol, T., & Kraus, N. (2004). Atypical brainstem representation of onset and formant structure of speech sounds in children with language-based learning problems. *Biological Psychology, 67*, 299-317. doi:10.1016/j.biopsycho.2004.02.002

Wier, C.C., Jesteadt, W., & Green, D.M. (1977). Frequency discrimination as a function of frequency and sensation level. *Journal of the Acoustical Society of America, 61*, 178-184.

Wightman, F., Allen, P., Dolan, T., Kistler, D. & Jamieson, D. (1989). Temporal resolution in children. *Child Development, 60*, 611-624.

Wilkinson, G. (1993). *Wide Range Achievement Test, 3rd Edition*. Wilmington, DW: Wide Range, Incorporated.

Willeford, J.A. (1985). Assessment of central auditory processing disorders in children. In M.L. Pinheiro & F.E. Musiek (Eds.), *Assessment of Central Auditory Dysfunction: Foundations and Clinical Correlates* (pp. 239-255). Baltimore, MD: Williams & Wilkins.

Willeford, J.A. & Burleigh, J.M. (1985). Behavior Manifestations. In *Handbook of Central Auditory Processing Disorders in Children* (pp. 49-59). Orlando, FL: Grune & Stratton, Inc.

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

Wright, B.A., Zecker, S.G., & McClelland, J.L. (2004). Learning problems, delayed development, and puberty. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 9942-9946.

Wright, H.N. (1978). Brief tone audiometry. In J. Katz (Ed), *Handbook of Clinical Audiology* (2nd ed., pp. 218-232). Baltimore, MD: The Williams & Wilkins Company.

Wolff, R., Hommerich, J., Riemsma, R. Antes, G., Lange, S. & Kleijnen, J. (2009). Hearing screening in newborns: Systematic review of accuracy effectiveness and effects of interventions after screening. *Archives of Disabilities in Childhood, 95*, 130-135. doi:10.1136/adc.2008.151092

XLfit (Version 5.1.1) [Computer software]. Surrey, United Kingdom: IDBS.

Yalcinkaya, F. & Keith, R. (2008). Understanding auditory processing disorders. The *Turkish Journal of Pediatrics, 50*, 101-105.

Yoshinaga-Itano, C., Johnson, C., Carpenter, K. & Brown, A. (2008). Outcomes of children with mild bilateral hearing loss and unilateral hearing loss. *Seminars in Hearing, 29*, 196-211.

Yost, W.A. (1993). Overview: Psychoacoustics. In W.A. Yost, A.N. Popper, & R.R. Fay (Eds), *Human Psychophysics* (pp. 1-12). New York: Springer-Verlag.

Yost, W.A. (2007). Auditory sensitivity. In *Fundamentals of Hearing: An Introduction* (pp. 143-157). Burlington, MA: Academic Press.

Zwicker, E. (1974). On a psychoacoustical equivalent of tuning curves. In E. Zwicker & E. Terhardt (Eds.), *Facts and Models in Hearing*. (pp. 132-141).

Zwislocki, J. (1960). Theory of temporal auditory summation. *Journal of the Acoustical Society of America, 32*, 1046-1060.

Appendices

Appendix A: Approval for Research Involving Human Participants

Office of Research Ethics

The University of Western Ontario

Western

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. P. Allen
Review Number: 09073E
Revision Number:
Protocol Title: Individual differences in auditory processing abilities.
Department and Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: CLLRNET
Approval Date: 22-Aug-02
End Date: 30-Sep-06
Documents Reviewed and Approved: UWO Protocol, Letters of Information, Consent
Documents Received for Information:

This is to notify you that the University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has received and granted full board approval to the above named research study on the date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:

a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;

b) all adverse and unexpected experiences or events that are both serious and unexpected;

c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB (Expedited): Dr. Paul Harding

Karen Kueneman, BA (Hons), Ethics Officer HSREB (Expedited)

Faxed: Y/N
Date: Aug 23/02

This is an official document. Please retain the original in your files.

UWO HSREB Ethics Approval 09073E Page 1 of 1

Western

Office of Research Ethics

The University of Western Ontario

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. P. Allen
Review Number: 09073E **Revision Number:** 3
Protocol Title: Individual differences in auditory processing abilities.
Department and Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: CLLRNET
Ethics Approval Date: September 6, 2006 **Expiry Date:** September 30, 2007
Documents Reviewed and Approved: Revised Study End Date
Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted expedited approval to the above named research study on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. John W. McDonald
Deputy Chair: Susan Hoddinott

Ethics Officer to Contact for Further Information

☒ Denise Grafton

cc: ORE File

This is an official document. Please retain the original in your files.

UWO HSREB Ethics Approval
2006-08-24 (HS-EXP)

09073E

Page 1 of 1

Appendix B: Letter of Information and Consent

Letter of Information for Parents/GuardiansStudy:
Individual Differences in Auditory Processing Abilities

Primary Investigator: Prudence Allen, Ph.D.
Research Associates: Chris Allan, M.Sc.
Place of Research: National Centre for Audiology, University of Western Ontario

Fall 2003

Dear Parent,

We are conducting a study of hearing and central auditory processing skills at the National Centre for Audiology located in the University of Western Ontario. Our interest is in discovering the individual differences between children on hearing and listening tasks. Your child is invited to participate in this study. We will have approximately 225 children participating in the study. Each child involved in the study will spend the entire day at the National Centre for Audiology participating in a variety of tests. All children involved in this study will participate in hearing and listening tests, language tests, learning and memory tests, as well as tests of attention. You will also be asked to complete, for your child, a case history form as well as behaviour and hearing/listening rating scales.

During the hearing and listening tests your child will sit comfortably in a soundproof room listening to different sounds or words while wearing earphones. Your child will be asked to repeat words or report what sounds they have heard. They will also complete one task that involves watching a computer screen and listening to sounds. The children are presented with three colourful cartoon fish that each make a sound. Your child will be asked to identify which cartoon made the sound that was different from the others. We will also be measuring your child's hearing by placing 4 electrodes on the surface of the skin (one behind each earlobe, one on the forehead, and one on the top of the head). During this test your child can relax, and is not required to do anything other than indicate the presence of the tone or beep that was different from the others. Children will also participate in language, learning, memory, and attentional testing. During these tests your child will be asked to point to pictures, answer questions verbally, and write or circle their answers.

While your child is participating in the study, you will be asked to complete some rating scales about your child's listening and attentional behaviours, as well as forms asking information about your child's medical and school history.

This study will involve no known risk to your child. The sounds your child will be hearing are usually as loud as conversational speech and will never be so loud as to be uncomfortable or damaging. Your child will experience little or no discomfort during this study. At times long term use of earphones can become uncomfortable however all attempts have been made to avoid this kind of discomfort. The use of electrodes during one of the auditory tests requires that we clean the skin with a small cleansing pad. During the cleaning process we gently rub the skin and this does not usually cause discomfort for children.

Participation in the study is voluntary. You and your child may refuse to participate, refuse to answer any questions, or withdraw from the study at any time.

The information gathered in this study will remain confidential at all times. When your child enters the study a 4-digit identification code will be assigned and this code is the only identifying information recorded on the test forms. No child will be identified in any analysis or publication, however if it is determined that your child may have hearing problems that require further attention you will be notified of this fact.

This letter is yours to keep. We would appreciate your permission to allow your child to participate. Please contact Chris Allan in our Child Hearing Research Lab to arrange an appointment if you do wish to have your child participate in this study. Due to the large number of tests and surveys used in this study (25) you may decide to complete the assessment over two days.

If you have further questions please contact me. If you have any questions about the conduct of this study or your rights as a research subject you may contact Susan Hoddinott, Director, Office of Research Ethics, The University of Western Ontario. Thank you for your time and consideration.

Yours sincerely,

Prudence Allen, Ph.D.
Associate Professor

CONSENT FORM

I have read the accompanying Letter of Information. The nature of the study has been explained to me and I agree to allow my

child,______________________________, to participate in this study.

All questions have been answered to my satisfaction.

Date: ___________________________________

Parent or Guardian's Signature: ___________________________________

Signature of Person Obtaining Informed Consent::_____________________

Child's Signature: ____

Child's Date of Birth: _______________________________________

Child's Present Grade Level: ________________________________

Child's School: ____

Child's Present Teacher: _____________________________________

Appendix C: Approval for Research Involving Human Participants

Office of Research Ethics

The University of Western Ontario

Western

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. P. Allen
Review Number: 13629E **Review Level:** Expedited
Review Date: September 26, 2007
Protocol Title: Children's performance on tests of auditory processing
Department and Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor:
Ethics Approval Date: October 17, 2007 **Expiry Date:** October 31, 2009
Documents Reviewed and Approved: UWO Protocol, Letter of Information and Consent for Parents, Letter of Information and Consent for Participants.
Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced study on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:

a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. John W. McDonald

Ethics Officer to Contact for Further Information

Grace Kelly

This is an official document. Please retain the original in your files.

cc: ORE File

UWO HSREB Ethics Approval - Initial
V.2007-10-12 (rptApprovalNoticeHSREB_Initial) 13629E Page 1 of 1

Appendix D: Letters of Information and Consent

Letter of Information for Adult Participants

Study: Children's performance on tests of auditory processing
Principal Investigator: Prudence Allen, Ph.D.
Research Associate: Chris Allan, M.Sc.
Place of testing: National Centre for Audiology, UWO

Winter, 2006/2007

Dear Participant,

You are being invited to participate, as part of a normal adult comparison group, in a study of hearing and auditory processing (listening). The objective of this project is to compare the usefulness of several different tests in the assessment of children's auditory skills. We plan to compare the performance of normal or typically developing children with children suspected of having or diagnosed as having an auditory processing deficit. In total there will be approximately children and 10 adults participating in this research study.

If you agree to participate, you will sit comfortably in a soundproof room listening to different sounds while wearing earphones. You will also complete listening tasks, using the same tests administered to the children, that involve watching a computer screen and listening to sounds. You will be presented with three colourful cartoon graphics that each make a sound. You will be asked to identify which cartoon made the sound that was different from the others by touching one of the graphics displayed on the computer touch-screen monitor. The responses will be recorded by the computer.

You will also have your hearing assessed by placing 4 electrodes on the surface of the skin (one behind each earlobe, one on the forehead, and one on the top of the head). During this test you can relax, and are not required to do anything. The use of electrodes during this auditory test requires that we clean the skin with a small cleansing pad. During the cleaning process we gently rub the skin but this does not usually cause discomfort.

Test sessions will last no longer than 3 hours (scheduled for your convenience) and testing may be divided into several sessions at your request. Free parking will be provided for the study.

This study will involve no known risk to you. The sounds you will be hearing are usually as loud as conversational speech and will never be so loud as to be uncomfortable or damaging. You will experience little or no discomfort during this study. At times long term use of earphones can become uncomfortable however all attempts will be made to avoid this kind of discomfort. Rest breaks will be provided at regular intervals as well as upon request to prevent fatigue or distraction due to hunger or thirst.

The information gathered during this study will remain confidential at all times. No individual listener will be identified in any analysis or publication, however, if it is determined that you may have hearing problems that require further attention you will be notified. During the study, a 4 character ID code will be used to reference each participant, rather than their full names. ID codes and corresponding full names of participants will be kept in a journal and locked in a cabinet. Only the local research team and the UWO HSREB may have access to the cabinet. The data will be kept as it is being collected and analyzed. Once the project is completed, all information containing participants' names and ID codes, including backup DVD's and paper documents, will be deleted and overwritten or destroyed by shredding. Upon publication, group data will be reported. If individual data is reported, references will be made to the ID code and age group only.

Participation in the study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time.

This letter is yours to keep. If you agree to participate please sign the attached form. You will receive a copy of the signed consent form. If you have any further questions you may contact me. If you have any questions about the conduct of this study or your rights as a research subject you may contact Susan Hoddinott, Director, Office of Research Ethics, The University of Western Ontario. Thank you for your time and consideration.

Sincerely,
Dr. Prudence Allen

Study: Children's performance on tests of auditory processing

<u>Adult Consent Form</u>

I have read Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Signature: ____

Name (please print): ____

Date: ____

Signature of Person Obtaining Informed Consent:______________________________

Telephone number: ____

Letter of Information for Parents

Study: **Children's performance on tests of auditory processing**

Principal Investigator: Prudence Allen, Ph.D.
Research Associate: Chris Allan, M.Sc.
Place of testing: National Centre for Audiology, UWO

Winter, 2006/2007

Dear Parent,

Your child is invited to participate in a study of hearing and auditory processing (listening). The objective of this project is to compare the usefulness of several different tests in the assessment of children's auditory skills. We plan to compare the performance of normal or typically developing children with children suspected of having or diagnosed as having an auditory processing deficit. In total there will be approximately 80 children participating in this research study. For one of the listening tests we will have a small group of 10 adults participating in the study for comparison purposes.

If you agree to participate your child, during the hearing and listening tests, will sit comfortably in a soundproof room listening to different sounds or words while wearing earphones. Your child will be asked to repeat words or report what sounds they have heard. They will also complete one or two listening tasks that involve watching a computer screen and listening to sounds. The children are presented with three colourful cartoon graphics that each make a sound. Your child will be asked to identify which cartoon made the sound that was different from the others by touching the graphic on the computer touch-screen monitor. The responses will be recorded by the computer.

A small group of children and the adults will also have their hearing assessed by placing 4 electrodes on the surface of the skin (one behind each earlobe, one on the forehead, and one on the top of the head). During this test the children can relax, and are not required to do anything. Only those parents and children that agree to participate in this part of the research study prior to entry into the project will undergo this particular testing. The use of electrodes during this auditory test requires that we clean the skin with a small cleansing pad. During the cleaning process we gently rub the skin but this does not usually cause discomfort for children.

Test sessions will last no longer than 3 hours (scheduled for your convenience) and testing may be divided into several sessions at your request. Free parking will be provided for the study. Children will be given a small toy or school supply in appreciation for their participation.

This study will involve no known risk to your child. The sounds your child will be hearing are usually as loud as conversational speech and will never be so loud as to be uncomfortable or damaging. Your child will experience little or no discomfort during this study. At times long term use of earphones can become uncomfortable however all attempts will be made to avoid this kind of discomfort. Rest breaks will be provided at regular intervals as well as upon request to prevent fatigue or distraction due to hunger or thirst.

The information gathered during this study will remain confidential at all times. No individual listener will be identified in any analysis or publication, however, if it is determined that your child may have hearing problems that require further attention you will be notified. During the study, a 4 character ID code will be used to reference each participant, rather than their full names. ID codes and corresponding full names of participants will be kept in a journal and locked in a cabinet. Only the local research team may have access to the cabinet and the Representatives of the University of Western Ontario Health Sciences Research Ethics Board may contact you or require access to your study-related records to monitor the conduct of the research. The data will be kept as it is being collected and analyzed. Once the project is completed, all information containing participants' names and ID codes, including backup DVD's and paper documents, will be deleted and overwritten or destroyed by shredding. Upon publication, group data will be reported. If individual data is reported, references will be made to the ID code and age only. Your child's birthdate will need to be retained for the study. Identifying the age of each participant is necessary to separate participants into age groups (preschool/ school-aged, adult) and in order to determine if differences in test results are consistent with expectations, or vary throughout groups due to age. Thus, the age identifiers are necessary to conduct data linkage with a high degree of accuracy.

Participation in the study is voluntary. You and/or your child may refuse to participate, refuse to answer any questions or withdraw from the study at any time. Once the data collection process is complete, it will not be possible to remove your data from the study, since the data will be anonymous.

This letter is yours to keep. If you agree to participate please sign the attached form. You will receive a copy of the signed consent form. If you have any further questions you may contact me. If you have any questions about the conduct of this study or your rights as a research subject you may contact the Director, Office of Research Ethics, The University of Western Ontario. Thank you for your time and consideration.

Sincerely,

Dr. Prudence Allen

Study: Children's performance on tests of auditory processing

Parent Consent Form

I have read Letter of Information, have had the nature of the study explained to me and

I agree to allow my child, ____, to participate. All questions have been answered to my satisfaction.

Date: ____

Parent or Guardian's Signature: ____

Parent or Guardian's Name : ____
(please print)

Signature of Person Obtaining Informed Consent:________________________________

Person Obtaining Informed Consent:____

Child's Signature: ____

Child's date of birth: ____

Curriculum Vitae

Name:	Chris Allan
Post-secondary Education and Degrees:	The University of Western Ontario London, Ontario, Canada 1978-1983 B.Sc.
	The University of Western Ontario London, Ontario, Canada 1983-1988 M.Sc.
	The University of Western Ontario London, Ontario, Canada 2003-2011 Ph.D.
Related Work Experience	Teaching Assistant The University of Western Ontario 2003-2009
	Research Associate The University of Western Ontario 2002-2011

Publications:

Allen, P. & Allan, C. (2007). Auditory processing disorders: Putting the "neural" back into sensorineural hearing loss. In R.C. Seewald & J.M. Bamford (Eds.), A Sound Foundation Through Early Amplification 2007: Proceedings of the Fourth International Conference (pp. 221-233). Stäfa, Switzerland: Phonak AG.

Allan, C.M., Campbell, W.N., Guptill, C.A., Stephenson, F.F., Campbell, K.E. (2006). A conceptual model for interprofessional education: The international classification of functioning, disability and health (ICF). Journal of Interprofessional Care, 20, 235-245.

Allen, P., Brogan, N. and Allan, C. (2004). Impact of noise on reading and vocabulary skills in Elementary School-aged Children. Lay Language Paper from the 147th Meeting of the Acoustical Society of America, New York, NY. www.acoustics.org/press/147th/allen.htm.