12-18-2014 12:00 AM

Measures of Acoustic Reflexes in Typically Developing Children and Children with Suspected Auditory Processing Disorder

Udit Saxena, *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

Measures of Acoustic Reflexes in Typically Developing Children and Children with Suspected Auditory Processing Disorder

(Thesis format: Integrated Article)

by

Udit Saxena

Graduate Program in Health & Rehabilitation Sciences

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

Abstract

A series of studies were conducted to examine the acoustic reflex in normal hearing adults, typically developing children and children with suspected auditory processing disorder (APD). Elevated acoustic reflex thresholds (ART) and shallower acoustic reflex growth functions (ARGF) were found in children with suspected APD in comparison to typically developing children and normal hearing adults. These effects were strongest in the crossed condition. There were no group differences for acoustic reflex latency (ARL) or acoustic reflex decay (ARD).

In all studies the children with suspected APD were divided into two groups based on the diagnosis made on the basis of a behavioral APD battery; (1) APD which included children who received APD diagnosis and (2) Clinical non-APD who did not receive APD diagnosis. Children in the clinical non-APD and APD groups had similar ART and ARGF abnormalities highlighting a potential weakness in relying strictly on behavioral tests in the assessment of children suspected of APD.

The effect of acoustic reflex activation on middle ear absorbance (MEA) and middle ear resonant frequency (MERF) was also investigated. It was found that the activation of the acoustic reflex resulted in a decrease of MEA between 226 and 1000 Hz, an increase MEA between 1000 and 2000 Hz and shift of MERF to a higher frequency. These changes in middle ear function may be critical to speech in noise perception. The effect of reflex activation was diminished in children with suspected APD.

Across studies, acoustic reflex measures including ART, ARGF and the effect of the reflex on MEA and MERF showed a trend suggesting age-related changes but the trends did not reach statistical significance. However, a significant developmental trend in ARTs was found when corrected for ear canal volume differences. These results suggest that acoustic reflex measures in clinical children should be compared with those of typically developing children rather adults.

Keywords

Acoustic reflex, acoustic reflex threshold, acoustic reflex growth function, acoustic reflex latency, acoustic reflex decay, auditory processing disorder, middle ear absorbance, middle ear resonant frequency.

Lists of Abbreviations

A

AAA	American Academy of Audiology
ANSI	American National Standards Institute
APD	Auditory Processing Disorder
ARD	Acoustic Reflex Decay
ARGF	Acoustic Reflex Growth Function
ARL	Acoustic Reflex Latency
ART	Acoustic Reflex Threshold
ASHA	American Speech-Language and Hearing Association

C

cc	Cubic centimetre
CN	Cochlear Nucleus

D

dB	Decibel
D-ART	Difference between crossed and uncrossed ART

E

ECV	Ear Canal Volume

H

HL	Hearing Level

M

MEA	Middle Ear Absorbance
MERF	Middle Ear Resonant Frequency
ml	Millilitre
msec	Millisecond
MSO	Medial Superior Olive

P

PVCN	Posterior Ventral Cochlear Nucleus
peSPL	Peak Equivalent Sound Pressure Level

R

RET SPL	Reference Equivalent Threshold Sound Pressure Level
RECD	Real Ear to Coupler Difference
RM-ANOVA	Repeated Measures Analysis of Variance

S

SD	Standard Deviation
SE	Standard Error
SL	Sensation Level
SMN	Stapedius motor neuron
SPL	Sound Pressure Level

Co-Authorship Statement

This thesis is comprised of six chapters. I am the main author for all the chapters as I was responsible for designing the methods of the experiments, collecting the data, statistical analysis of the results and writing the manuscripts. Drs Chris Allan and Prudence Allen are co-authors in chapters 2-5 as they participated in study design and analyses. Additionally, Dr Chris Allan contributed to the data collection and was responsible for recruiting and assessing children's auditory processing skills.

Dedication

I dedicate this work to the two most wonderful ladies

Drs Prudence Allen and Chris Allan

For all the support, motivation, guidance and the motherly warmth

AND

My Angel “Suhani”

&

Srikanta Da

Acknowledgments

I would to acknowledge my advisors Drs David Purcell and Hanif Ladak for their valuable advices during the course of this research.

Drs Ewan Macpherson, Susan Scollie and Vijay Parsa for clearing my scientific doubts I had in their areas of expertise.

David Grainger, David Lee, Lucy Keiffer and Steve Beaulac for all the technical and administrative support.

Sangam for critical discussions during coffee breaks.

The University of Western Ontario.

Beautiful CANADA.

Table of Contents

List of Tables

List of Figures

Chapter 1

1 Introduction: Auditory Processing Disorder and Acoustic Reflex

1.1 Auditory processing disorder

The term “Auditory Processing Disorder” (APD) suggests difficulties in the processing of auditory information by the central auditory nervous system (American Speech-Language-Hearing Association [ASHA], 2005). Individuals with APD form a highly complex group with large individual differences. APD can affect children, adults, or elderly persons and its etiology and symptoms may vary across individuals (American Academy of Audiology [AAA], 2010; ASHA, 2005).

1.1.1 Children with suspected APD: Symptoms and characteristics

Children with suspected APD are often described as having difficulty hearing even in the presence of normal hearing sensitivity. Difficulty understanding speech in the presence of background noise, being easily distracted in complex acoustic environments, problems following multiple commands and slow comprehension of simple auditory information are frequently reported symptoms (Benson, Seaton & Johnson, 1997; Keith, 1999; Jerger & Musiek, 2000). APD may lead to, or may be associated with, attention, language, reading, learning and cognitive disorders, however the nature of the relationships are not well understood (AAA, 2010; ASHA, 1996, 2005). The combination of APD and its possible comorbid conditions have the potential to negatively impact a child’s academic success and social functioning (AAA, 2010).

1.1.2 APD: Prevalence in school age children and etiologies

APD has an estimated prevalence of 2% to 7% in school aged children (Bamiou, Musiek & Luxon, 2001; Chermak & Musiek, 1997). Chermak (2002) in summarizing possible etiologies of APD in children based on previous reports (e.g. Chermak & Musiek, 1997, Musiek, Baran & Pinheiro, 1992; Musiek, Gollegly & Ross, 1985; Musiek, Kibbe & Baran, 1984) suggested that neuromorphologic disorders are the likely cause behind 65% to 70% of the problem of children who are diagnosed with APD. Neuromaturational delay may account for 25% to 30%, and neurologic disorders, disease or damage for 5%.

1.1.3 APD: Diagnosis

Diagnosing APD in a child can be a challenging task for the audiologist. ASHA (2005) recommended a test battery approach that includes tasks to assess sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal processing and performance in presence of competing acoustic signals. A positive diagnosis of APD is to be made if a child performs poorly ($\geq$ 2 standard deviations below age expected values) on at least 2 auditory tests. Since there is no gold standard on the selection of tests, audiologists can choose from a wide range of tests. This could lead to a high variability in the criterion for APD diagnosis across clinics and in research (Allen & Allan, 2014). Also, the most commonly used tests are behavioral (Emanuel, Ficca & Korczak, 2011) and may be strongly linked to underlying language and cognitive abilities (Allen & Allan, 2014). Other possible limitations of behavioral tests include the possibility that young children may not understand test instructions, the mode of response required by the test may not be appropriate, and a lack of attention and motivation in young children may limit performance. Many of the behavioral tests are unavailable in languages other than English and many do not have normative data for very young children (AAA, 2010; ASHA, 2005; Jerger & Musiek, 2000).

Objective tests have been recommended by AAA (2010), ASHA (2005) and Jerger and Musiek (2000) but these tests have not been the preferred choice among audiologists for APD assessment (Emanuel et al., 2011). However the ability of the objective tests to estimate a specific site of dysfunction and the fact that objective tests are not influenced by factors such as language or procedure can make them highly effective in the assessment of APD, especially in children.

1.1.4 APD: Neural basis

The central auditory pathway stretches from the neural fibers originating in the cochlea to the auditory cortex. Each anatomical nucleus along this pathway serves one or more central auditory processes and auditory processing disorders can result from deficit in one or more of these neural structures (Bamiou, Musiek & Luxon, 2001; Moore, 2006). The auditory brainstem is the locus of the earliest processing of auditory information as it ascends the auditory tract. Trouble with the processing of sound at the brainstem level may lead to poor decoding at higher neural centres and thus result in perceptual difficulty.

Objective measurements of acoustic reflexes, contralateral suppression of otoaoustic emissions and auditory brainstem responses have indicated auditory brainstem abnormalities in children with APD symptoms. Reduced contralateral suppression of transient evoked otoacoustic emissions is reported in children with suspected APD when compared to normal hearing children (Muchnik et al., 2004; Sanches & Carvallo, 2006). However, Butler, Purcell and Allen (2011) contradict these findings as they found similar contralateral suppression of distortion product otoacoustic emission in children with APD and normal hearing children.

Abnormalities in auditory brainstem responses in children with suspected APD are demonstrated in several studies. Significantly reduced amplitude of the binaural interaction component of the auditory brainstem responses (Gopal & Pieral, 1999) shallower slopes of waves I through V (Gopal & Kowalski, 1999) and delayed wave V (Jisra, 2001) have been found in children with suspected APD in comparison to normal hearing children. Kraus and colleagues (Banai, Nicol, Zecker & Kraus, 2005; Cunningham, Nicol, Zecker, Bardlow & Kraus, 2001; King, Warrier, Hayes & Kraus, 2002; Wible, Nicol & Kraus, 2004) have also suggested atypical speech evoked auditory brainstem responses in one third of the children with language learning disorders who also have symptoms of APD.

Allen and Allan (2007, 2014) investigated acoustic reflex and auditory brainstem responses in children with suspected APD. They reported 65% of the children tested showed clinically significant abnormalities in either acoustic reflex or auditory brainstem responses. High percentages of reflex abnormalities in children with suspected APD are also reported by Meneguello et al. (2001) and Thomas, McMurry and Pillsbury (1985).

Based on the studies described it is apparent that many children with suspected APD may have abnormalities in brainstem function. The acoustic reflex is a sensitive measure of auditory brainstem dysfunction (Gelfand, 2005; Jerger & Jerger, 1977; Silman, 1984) but only limited literature on acoustic reflexes, specific to the reflex thresholds, is available in children with suspected APD. Detailed studies of the acoustic reflex measures in children with suspected APD can provide important information about the auditory brainstem in this clinical population. These studies will also provide insight into the relationship between the suggested functional role of acoustic reflexes in perceiving speech in the presence of noise and children with suspected APD.

1.2 The acoustic reflex

The middle ear muscle reflex is one of the primary feedback mechanisms of the auditory system (Liberman & Guinan, 1998). The reflex results largely from the contraction of the stapedius and tensor tympani muscles following acoustic stimulation of the ears. In most animals both the stapedius and tensor tympani muscles contribute to the reflex in response to auditory stimuli (Moller 1984; Mukerji, Windsor & Lee, 2010). In humans, it is predominantly the stapedius muscle while the contraction of the tensor tympani muscle occurs primarily during the startle response to intense sounds or to non-auditory stimuli (Borg, 1968; Borg, Counter & Rosler, 1984; Moller, 1984; Mukerji et al., 2010).

1.2.1 Anatomy of the acoustic reflex pathway

The acoustic reflex occurs from stimulation to both crossed and uncrossed reflex pathways. The anatomy of the reflex pathway is well described in the literature (Moller, 1984; Mukerji et al., 2010). Anatomical structures include the peripheral auditory system (external ear, middle ear and the cochlea), the auditory nerve, two nuclei of the auditory brainstem (the cochlear nucleus [CN] and the superior olivary complex [SOC]), the facial motor nucleus and nerve and the stapedius muscle (Figure 1.1). The central segment of the acoustic reflex arc initiates with the projection of type I spiral ganglion neurons (afferents from inner hair cells) to the cochlear nucleus. Interneurons responsible for the acoustic reflex lie in the posterior ventral cochlear nucleus (PVCN). Interneurons from the PVCN innervate the stapedius motor neuron (SMN) of the facial nerve through direct and indirect projections. Direct projection involves the innervation of SMN directly by PVCN interneurons. Indirect projection includes projection of PVCN interneurons to the SMN through the superior olivary complex. It is the medial superior olive (MSO) that is primarily involved in the acoustic reflex. The PVCN supplies second order neurons to the ipsilateral MSO and contralateral MSO. The MSO finally sends third order neurons to the SMN of the ipsilateral facial nerve (for uncrossed reflex) and SMN of the contralateral facial nerve (for crossed reflex).

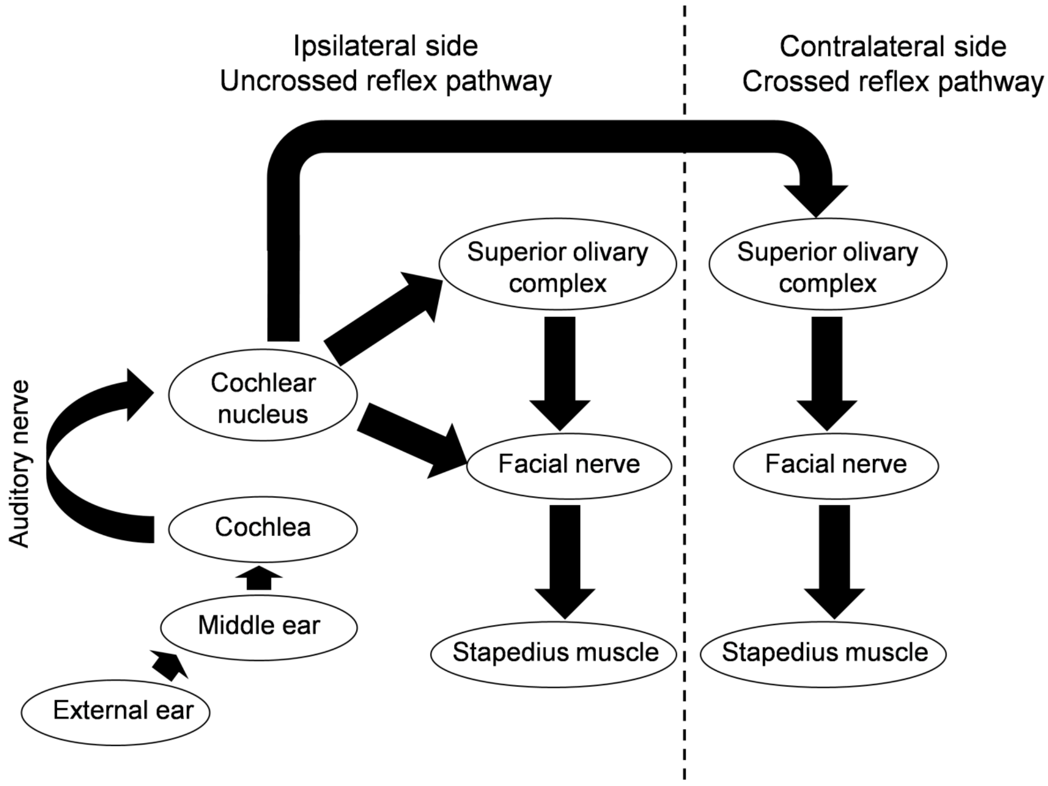

Figure 1.1: The acoustic reflex pathway

The main function of the auditory brainstem is to preserve and extract spectral and temporal information for processing in the higher auditory system (Irvine, 1992). The superior olivary complex is also the first nucleus of the auditory system where binaural inputs interact (Brugge, 1992). In the presence of a normal peripheral auditory system any abnormality in the acoustic reflex may indicate a deficit in the functioning of the auditory nerve, the cochlear nucleus or the superior olivary complex. Therefore the information provided by the acoustic reflex testing in individuals with auditory processing deficits can be useful in determining the underlying neural deficit.

1.2.2 Functions of the acoustic reflex

The functional importance of the acoustic reflex has been discussed for many years. Several hypotheses are offered regarding its role including primarily its roles in protecting against inner ear damage from loud sounds and its facilitation in speech perception in the presence of noise (Borg et al., 1984). It has also been suggested to aid in the perception of faint sounds, it improves temporal resolution and it enhances auditory attention.

Support for the protective function of acoustic reflex comes from studies that investigated the relationship between elicitation of the acoustic reflex and temporary threshold shift following noise exposure (Cohen & Bauman, 1964; Mills & Lilly, 1971; Ward, 1962; Zakrisson, Borg, Liden & Nilsson, 1980). Studies have shown that the presence of a normal acoustic reflex is associated with reduced temporary threshold shifts. But the protective role of the acoustic reflex is not universally supported (Fletcher, 1962; Henderson, Subramaniam, Papazian & Spongr, 1994; Ryan, Bennett, Woolf & Axelsson, 1994). It is suggested that the acoustic reflex may provide only limited protection for loud sounds because its onset is most often over 100 msec (Borg , 1982; Gorga & Stelmachowicz, 1983; Hung & Dallos, 1972; Qiu & Stucker, 1998).This delay makes the acoustic reflex relatively meaningless in preventing damage from impulse noise or stimulus onsets. Also the acoustic reflex undergoes adaptation if the sound is present for very long durations (Gelfand, 2005) and therefore the protective function, if present, is limited.

The role of the reflex in enhancing speech perception in noise is more likely. Simmons (1964) explained that the acoustic reflex helps in improving speech intelligibility especially in the presence of noise by attenuating low frequency information. The reflex modulates the amplitude and frequency of sounds which therefore may increase alertness in listeners, allow better separation of background noise and signal and enhance attention to the signal. Aiken, Andrus, Bance and Phillips (2013) suggested that the acoustic reflex may help in speech perception in noise by preventing upward spread of masking at moderate noise levels. De Andrade et al. (2011) and Colletti, Fiorino, Verlato and Carner (1992) found that the acoustic reflex is important for better performance in speech discrimination and frequency selectivity tasks, respectively. Dorman, Cedar, Hannley and Leek (1986) reported that the activation of the acoustic reflex in normal hearing listeners improves their vowel recognition. On the contrary, Phillips, Stuart and Carpenter (2002) found no role of the reflex in word recognition in quiet but suggested that role of reflex in speech perception could be restricted to the adverse listening conditions including listening in noise environment. Borg and Zakrisson (1974) found greater masking in the ears with acute stapedius muscle paralysis in comparison to the ear with normal acoustic reflexes when the stimulus was presented above reflex thresholds. Similar masking was reported in both the ears for the stimulus presentations below the acoustic reflex threshold.

1.2.3 Measures of acoustic reflex

There are several measurable characteristics of the acoustic reflex, each of which provides important details about the reflex activity. The reflex threshold is the minimum intensity level of the reflex activator stimulus at which the acoustic reflex activates. At threshold, the magnitude of the reflex is observable as a small change in the acoustic compliance of the middle ear. Presentation of stimuli above the threshold results in a greater magnitude. The magnitude of the reflex increases with increase in stimulus level until an asymptote, or maximum compliance change is reached. This generally occurs within 30 dB of reflex threshold. The relationship between reflex magnitude and activator stimulus level can be described by an acoustic reflex growth function. Measures can also be made of the time course of the reflex activation. Acoustic reflex latency refers to the time taken by the stapedius muscle to contract after the onset of the stimulus. The amplitude of the reflex reaches its maximum magnitude after the activator is presented for around 250 msec. The reflex then undergoes adaptation and its amplitude decreases if the stimulation continues for a longer duration. This characteristic of acoustic reflex is known as acoustic reflex decay.

Individuals with the disorders of auditory nerve and auditory brainstem lesions have shown absent or elevated reflex thresholds (Anderson, Barr & Wedenberg, 1970; Johnson, 1977; Mangham, Lindeman & Dawson, 1980), low reflex amplitudes (Mangham et al., 1980), shallower growth functions (Harrison, Silman & Silverman, 1989; Mangham et al., 1980; Silman, Popelka & Gelfand, 1978;), prolonged reflex latencies (Clemis & Sarno, 1980; Jerger & Haynes, 1983; Mangham et al., 1980) and greater or earlier reflex decay (Anderson et al., 1970; Mangham et al., 1980; Olsen, Noffsinger & Kurdziel, 1975)

Absent or elevated reflexes would indicate no reflex activity or that reflex activity is only initiated at higher stimulus levels. Low reflex amplitude and shallower growth of the reflex magnitude may suggest that the acoustic reflex is weak. Longer reflex latencies would mean a delay in the activation of acoustic reflex and greater or earlier decay may suggest that the reflex is only providing limited benefit. Abnormalities in one or more of these characteristics of the reflex, if present, may also therefore suggest limited benefit in speech in noise perception.

Despite the importance of the acoustic reflex in assessing auditory nerve and brainstem disorders and its potential importance for speech perception in the presence of noise, investigations of reflex in children with suspected APD are limited. Published studies report only reflex thresholds (Allen & Allan, 2007, 2014; Meneguello et al., 2001; Thomas et al., 1985). Further Investigations of other characteristics of the reflexes may provide greater information about the potential role in children with suspected APD.

Adult and child differences in acoustic reflexes have been investigated for reflex threshold, amplitude and decay. Habener and Snyder (1974) found lower reflex amplitude and elevated reflex thresholds in normal hearing children (aged 3 to 19 years) when compared to the young adults (aged 19 to 29 years) but no adult-children difference was found in reflex decay. Jerger, Jerger and Mauldin

(1972), Jerger, Hayes, Anthony and Mauldin (1978) and Osterhammel and Osterhammel (1979) have suggested higher thresholds in children (aged 7 to 15 years) when compared to adults. The reason for adult-children differences in reflex amplitudes and threshold are not well understood. A possible explanation could be the differences in the characteristics of the ear canal and middle ear static compliance that develop until puberty (Abdala & Keefe, 2012; Obake, Tanaka, Hamada, Miura & Funai, 1988). However the relationship between these factors and the acoustic reflex has not been investigated.

The acoustic reflex is bilateral with stimulation to either ear its effect can be measured in a crossed and uncrossed configuration referencing stimulus or measurement ear. Differences in crossed and uncrossed measures are reported in some studies and the suggestion is generally that the crossed pathways are weaker showing higher reflex thresholds (Fria, LeBlanc, Kristensen & Alberti, 1975; Gelfand, 2005; Jerger et al., 1978; Moller, 1961, 1962). The growth of the reflex with changes in stimulus magnitude is reported to be shallower for crossed stimulation in comparison to those with uncrossed responses (Jerger et al., 1978; Moller, 1961). Decay also differs in crossed and uncrossed condition. Lilly, Mekaru and Chudnow (1983, cited in: Wilson, Shanks & Lilly, 1984) reported that uncrossed reflexes had an earlier onset of reflex decay than reflexes in the crossed condition. Oviatt and Kileny (1979) suggested greater reflex decay for uncrossed stimulation in comparison to crossed stimulation but a significant difference was not found. Allen and Allan (2014) highlighted that acoustic reflex abnormalities in children with suspected APD are more likely to occur in the crossed pathways in children with this clinical disorder. This is similar to reports of reflexes in brainstem disorders which also shown abnormalities specific to the crossed pathways (Griesen & Rasmussen, 1970; Jerger & Jerger, 1977). These findings reflect the importance of the estimation of acoustic reflex measures in both crossed and uncrossed condition while using acoustic reflex in the auditory assessment.

1.3 Thesis purpose and chapter outline

Previous reports have suggested auditory brainstem abnormalities may be seen in some children with suspected APD. Acoustic reflexes have proven to be an important measure to assess auditory brainstem function. But investigations into acoustic reflexes in children with suspected APD are few and largely limited to the measure of acoustic reflex thresholds. The primary aim of this thesis is to better understand the relationship between acoustic reflex measures and children with suspected APD. In the first study (chapter 2), acoustic reflex thresholds were investigated in children with suspected APD to confirm previous findings of abnormal thresholds in children with suspected APD. This study also examined real ear corrections on threshold estimates and the role of static compliance. The second study was aimed at understanding the acoustic reflex growth function (chapter 3) which may be more sensitive to auditory pathology than a single threshold estimate. In the third study acoustic reflex latencies and decay were investigated to determine if there were pathology or age-related differences in the time course of the reflex (chapter 4). And finally, the last study examined the impact of the acoustic reflex on the absorbance and resonant frequency of the middle ear (chapter 5).

The diagnosis of APD can be a difficult task because there is no gold standard for diagnosis. Although professional associations suggest a test battery approach, individual clinicians are free to select tests from a large number that are available and often clinicians limit their test selection to behavioral measures, often examining some aspects of degraded speech perception or temporal pattern recognition (Emanuel et al. 2011). Yet Allen and Allan (2014), found that using a battery of such tests often failed to diagnose children as APD when referred for listening difficulties yet these children were found to show clinically significant abnormalities in auditory brainstem responses or reflex data suggesting some level of neural dysfunction that was missed with a test battery restricted to behavioral speech and pattern recognition tests. Therefore, in the studies included in this thesis, children with suspected APD were divided into two groups: (1) the APD group included children who were diagnosed as having APD based on a behavioral test battery of tests including Staggered Spondaic Word test (Katz, 1998), the Pitch Pattern Sequence Test (Pinheiro, 1977), the Words in Ipsilateral Competition test (Ivey, 1969, 1987) and two custom tests of frequency discrimination and gap detection; and (2) the clinical non-APD group included children who were referred for APD assessment but who were not diagnosed as APD based on this typical clinical battery. This provided the opportunity to investigate auditory brainstem functioning using acoustic reflexes in both the groups of children who reported listening problems.

Because there is generally a lack of published data on acoustic reflexes in children, each study also included a group of typically developing children and normal hearing adults. Most published studies and clinical normative have compared acoustic reflexes in clinical populations to those of normal hearing adults. The inclusion of typically developing children as well as adults allowed for the evaluation of potential age related effects.

1.4 References

Abdala, C., & Keefe, D. H. (2012). Morphological and functional ear development. In L. A. Werner, R. R Fay & A. N. Popper (Eds.), *Human Auditory Development* (pp. 19-59). New York: Springer.

Aiken, S. J., Andrus, J. N., Bance, M., & Phillips, D. P. (2013). Acoustic Stapedius Reflex Function in Man Revisited. *Ear and hearing*, *34*(4), e38-e51.

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. & Allan, C. (2014). Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

American Academy of Audiology [AAA]. (2010). American Academy of Audiology Clinical Practice Guidelines:Diagnosis, Treatment and Management of Children and Adults with Central auditory Processing Disorder. Retrieved from http:// www.audiology.org/resources/

American Speech-Language-Hearing Association. (1996). Central auditory processing: Current status of research and implications for clinical practice. *American Journal of Audiology*, *5*, 41-54.

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

Anderson, H., Barr, B. &Wedenberg, E. (1970). Early diagnosis of VIIIth-nerve tumours by acoustic reflex tests. *ActaOto-Laryngologica Supplement, 263,* 232-237.

Banai, K., & Kraus, N. (2007). Neurobiology of (central) auditory processing disorder and language-based learning disability. In G. D. Chermak & F. E. Musiek (Eds.), Handbook of (central) auditory processing disorders (pp. 89-116). San Diego: Plural Publishing.

Banai, K., Nicol, T., Zecker, S. G., & Kraus, N. (2005). Brainstem timing: implications for cortical processing and literacy. *The Journal of Neuroscience*,*25*(43), 9850-9857.

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.

Benson, P. V., Seaton, J. B., & Johnson, C. D. (1997). Educational audiology handbook. San Diego, CA: Singular.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *ActaOto-laryngologica, 66*, 461-472.

Borg, E. (1982). Time Course of the Human Acoustic Stapedius Reflex: A Comparison of Eight Different Measures in Normal-hearing Subjects. *Scandinavian audiology*, *11*(4), 237-242.

Borg, E. Counter, S. A. &Rosler, G. (1984). Theories of middle ear muscle function. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Borg, E., & Zakrisson, J. E. (1974). Stapedius reflex and monaural masking. *Actaoto-laryngologica*, *78*(1-6), 155-161.

Brugge, J. F. (1992). An overview of central auditory processing. In: A. N. Popper & R.R. Fay (Eds.), *The mammalian auditory pathway: Neurophysiology* (pp. 153-231). New York: Springer

Butler, B. E., Purcell, D. W., & Allen, P. (2011). Contralateral inhibition of distortion product otoacoustic emissions in children with auditory processing disorders. *International journal of audiology*, *50*(8), 530-539.

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

Chermak, G. D., & Musiek, F. E. (1997). *Central auditory processing disorders: New perspectives*. San Diego, CA: Singular.

Clemis, J.D. &Sarno, C.N. (1980). The acoustic reflex latency test: Clinical application. *Laryngoscope*, 90, 601-611.

Cohen, A., & Baumann, K. C. (1964). Temporary Hearing Losses following Exposure to Pronounced Single-Frequency Components in Broad-Band Noise.*The Journal of the Acoustical Society of America*, *36*(6), 1167-1175.

Colletti, V., Fiorino, F.G., Verlato, G. &Carner, M. (1992). Acoustic reflex in frequency selectivity: Brain stem auditory evoked response and speech discrimination. In J. Katz, N.A. Stecker& D. Henderson (Eds.). *Central Auditory Processing: A Transdisciplinary* View (pp. 39-46). St. Louis, MO: Mosby - Year Book, Incorporated.

Cunningham, J., Nicol, T., Zecker, S. G., Bradlow, A., & Kraus, N. (2001). Neurobiologic responses to speech in noise in children with learning problems: deficits and strategies for improvement. *Clinical Neurophysiology*, *112*(5), 758-767.

De Andrade, K.C.L., Camboim, E.D., Soares, I.D.A., Peixoto, M.V.D.S., Neto, S.C., Menezes, P.D.L. (2011). The importance of acoustic reflex for communication. *American Journal of Otolaryngology – Head and Neck Medicine and Surgery, 32*, 221-227.

Dorman, F., Lindholm, J. M., Hannley, M. T., & Leek, M. R. (1987). Vowel intelligibility in the absence of the acoustic reflex : Performance-intensity characteristics. *The Journal of the Acoustical Society of America81(2),* 562–564.

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.

Fletcher, J. L. (1962). Reflex response of middle-ear muscles : Protection of the ear from noise. *Sound, 1 (2),* 17–23.

Fria, T., LeBlanc, J., Kristensen, R., &Alberti, P. W. (1974). Ipsilateral acoustic reflex stimulation in normal and sensorineural impaired ears: a preliminary report. *Canadian journal of otolaryngology*, *4*(4), 695-703.

Gelfand, S.A. (2005). The acoustic reflex. In J. Katz (Ed.), *Handbook of clinical audiology: Fifth Edition* (pp: 205-232). Baltimore, MD: Lippincott Williams & Wilkins.

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.

Gopal, K.V. &Pierel, K. (1999). Binaural interaction component in children at risk for central auditory processing disorders. *Scandinavian Audiology*, 28, 77-84.

Greisen, O., & Rasmussen, P. E. (1970). Stapedius muscle reflexes and oto-neurological examinations in brain-stem tumors. *Acta oto-laryngologica*, *70*(5-6), 366-370.

Habener, S. A., & Snyder, J. M. (1974). Stapedius reflex amplitude and decay in normal hearing ears. *Archives of Otolaryngology*, *100*(4), 294-297.

Harrison, T., Silman, S. & Silverman, C.A. (1989). Contralateral acoustic reflex growth function in a patient with a cerebellar tumor: A case study. *Journal of Speech and Hearing Disorders, 54*, 505-509.

Henderson, D., Subramaniam, M., Papazian, M., &Spongr, V. P. (1994). The role of middle ear muscles in the development of resistance to noise induced hearing loss. *Hearing Research,74*, 22–28.

Hung, I. J. &Dallos, P. (1972). Study of the acoustic reflex in human beings. I. Dynamic characteristics. *The Journal of the Acoustical Society of America, 52 (4), 1972-80.*

Irvine, D. R. (1992). Physiology of the auditory brainstem. In: A. N. Popper & R.R. Fay (Eds.), *The mammalian auditory pathway: Neurophysiology* (pp. 153-231). New York: Springer

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.

Jerger, J., Jerger, S., & Mauldin, L. (1972). Studies in impedance audiometry: I. Normal and sensorineural ears. *Archives of Otolaryngology, 96,* 513-523.

Jerger, J., Hayes, D., Anthony, L. & Mauldin, L. (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Monographs in Contemporary Audiology, 1*, 1-20.

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.

Jerger, J., & Hayes, D. (1983). Latency of the acoustic reflex in eigth nerve tumor. *Archives of Otolaryngology, 109,* 1-5.

Jerger, S., & Jerger, J. (1977). Diagnostic value of crossed vs uncrossed acoustic reflexes: Eighth nerve and brain stem disorders. *Archives of Otolaryngology*, *103*(8), 445-453.

Jerger, J., & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing disorders in schoolaged children. *Journal of American Academy Audiology*, *11*, 467–74.

Johnson, E.W. (1977). Auditory test results in 500 cases of acoustic neuroma. *Archives of Otolaryngology, 103*, 152-158.

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

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

King, C., Warrier, C. M., Hayes, E., & Kraus, N. (2002). Deficits in auditory brainstem pathway encoding of speech sounds in children with learning problems. *Neuroscience letters*, *319*(2), 111-115.

Liberman, M. C., &Guinan, J. J. (1998). Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlearefferents. *Journal of Communication Disorders*, *31*(6), 471–82. Linares, A. E. &Carvallo, R. M. M. Acoustic reflex latency in children with auditory prossessing disorder. (2004). *International Archives of Otorhinolaryngology*. 8(1).

Mangham, C.A. & Lindeman, R.C. (1980). The negative acoustic reflex in retrocochlear disorders. *Laryngoscope, 90*, 1753-1761.

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian Journal of Otorhinolaryngology*. 67 (7), 2001.

Mills, J. H., & Lilly, D. J. (1971). Temporary threshold shifts produced by pure tones and by noise in the absence of an acoustic reflex. *The Journal of the Acoustical Society of America*, *50*(6B), 1556-1558.

Moller, A. R. (1961). Bilateral contraction of the tympanic muscles in man examined by measuring acoustic impedance-change. *The Annals of otology, rhinology, and laryngology*, *70*, 735.

Moller, A.R. (1962). Acoustic reflex in man. *The Journal of the Acoustical Society of America*, *34*, 1524-1534.

Moller, A. R. (1984). Neurophysiological basis of the acoustic middle ear reflex. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Moore, D. R. (2006). Auditory processing disorder (APD): Definition, diagnosis, neural basis, and intervention. *Audiological Medicine*, *4*(1), 4-11.

Muchnik, C., Roth, D.A., Othman-Jebara, R., Putter-Katz, H., Shabtai, E.L. &Hildesheimer, M. (2004). Reduced medial olivocochlear bundle system function in children with auditory processing disorders. *Audiology & Neuro-Otology, 9*, 107-114. doi: 10.1159/000076001

Mukerji, S., Windsor, A. M., & Lee, D. J. (2010). Auditory brainstem circuits that mediate the middle ear muscle reflex. *Trends in Amplification*, *14*(3), 170–91.

Musiek, F. E. & Lee, W. W. (1997). Conventional and maximum length sequences: Middle latency response in patients with central nervous system lesions. *Journal of American Academy of Audiology, I8:173-180.*

Okabe, K., Tanaka, S., Hamada, H., Miura, T., & Funai, H. (1988). Acoustic impedance measurement on normal ears of children. *Journal of the Acoustical Society of Japan (E)*, *9*(6), 287-294.

Olsen, W.O., Noffinger, D. &Kurdziel, S. (1975). Acoustic reflex and reflex decay. Occurrence in patients with cochlear and eighth nerve lesions. *Archives of Otolaryngology, 101*, 622-625.

Osterhammel, D., &Osterhammel, P. (1979). Age and sex variationsfor the normal stapedial reflex thresholds and tympanometric compliance values. *Scandinavian Audiology*, *8*, 153-158.

Oviatt, D. L., &Kileny, P. (1984). Normative characteristics of ipsilateral acoustic reflex adaptation. *Ear and hearing*, *5*(3), 145-152.

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

Ryan, A. F., Bennett, T. M., Woolf, N. K., &Axelsson, A. (1994). Protection from noise-induced hearing loss by prior exposure to a nontraumatic stimulus : Role of the middle ear muscles. *Hearing Research*, *72*, 23–28.

Sanches, S.G.G. &Carvallo, R.M. (2006). Contralateral suppression of transient evoked otoacoustic emissions in children with auditory processing disorder. *Audiology &Neurotology, 11*, 366-372.

Silman, S. (1984).*The acoustic reflex: Basic principle and clinical applications.* Orlando: Academic press.

Silman, S., Popelka, G.R. &Gelfand, S.A. (1978). Effect of sensorineural hearing loss on acoustic stapedius reflex growth functions. *The Journal of the Acoustical Society of America, 64*, 1406-1411.

Simmons, F. B. (1964). Perceptual theories of middle ear muscle function. *The Annals of otology, rhinology, and laryngology*, *73*, 724-739.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope, 95*, 811-817.

Ward, W. D. (1962). Damage-Risk Criteria for Line Spectra. *The Journal of the Acoustical Society of America*, *34*(10), 1610-1619.

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*(3), 299-317.

Zakrisson, J. E., Borg, E., Liden, G., & Nilsson, R. (1980). Stapedius reflex in industrial impact noise: fatigability and role for temporary threshold shift (TTS).*Scandinavian audiology. Supplementum*, (Suppl 12), 326-334.

Chapter 2

2 Acoustic Reflexes in Normal Hearing Adults, Typically Developing Children and Children with Suspected Auditory Processing Disorder: Thresholds, Real Ear Corrections and the role of Static Compliance on Estimates

2.1 Introduction

The Acoustic Reflex Threshold is defined as the minimum stimulus intensity at which the stapedius muscle contracts. Reflex thresholds are used diagnostically in clinical audiology, often to determine if a hearing loss is of cochlear or retrocochlear origin, but lesions anywhere in the auditory system can cause reflex abnormalities (Gelfand, 1984, 2005). Abnormal reflexes are usually interpreted along with the results of other auditory tests in order to determine the site of dysfunction. Abnormalities in reflexes thresholds due to middle ear or cochlear dysfunction are generally interpreted based on the results of pure-tone audiometry and tympanometry. An air-bone gap of as little as 30 dB in the stimulus ear may make it impossible to elicit a reflex simply because a sufficient excitation level cannot be reached within the limits of most equipment. In the probe ear even a mild middle ear pathology may be sufficient to make it impossible to measure change in impedance associated with reflex activation even if it occurs. With cochlear pathologies, reflexes are generally within the expected range unless a severe loss of hearing is present in which case thresholds are elevated or absent.

Reflex abnormalities associated with disorders of the auditory nerve or brainstem, i.e. retrocochlear pathology, may be more complex and often requires comparison of crossed and uncrossed responses (Jerger & Jerger, 1977). When the auditory nerve is affected, reflexes are often elevated or absent with stimulation to the affected ear regardless of the degree of hearing loss (e.g. Anderson, Barr & Wedenberg, 1970; Ferguson et al., 1996; Jerger, Harford, Clemis & Alford, 1974; Mangham, Lindeman & Dawson, 1980; Prasher & Cohen, 1993; Thomsen & Terkildsen, 1975). When there is an elevation or absence in thresholds in the presence of significant sensorineural hearing loss the diagnosis of cochlear versus retrocochlear pathology may be more difficult. Generally reflex thresholds of 95 dB HL or higher are taken as an indication of retrocohlear pathology (Anderson, Barr and Wedenberg (1969) cited in: Silman & Gelfand, 1981). Gelfand and colleagues (Silman & Gelfand,1981; Gelfand, Scehwander & Silman, 1990) estimated the 90th percentile cut-off for reflex thresholds at 500, 1000 and 2000 Hz in normal hearing adults and adults with cochlear impairment to fall at 95, 100 and 100 dB HL, respectively if the hearing thresholds are within normal limits ($\leq$ 15 dB HL). Presently, reflex thresholds beyond these cutoff values are used in clinics for determination of reflex abnormalities of retrocochlear origin (Gelfand, 2005).

Recently, Allen and Allan (2007, 2014) reported abnormal reflexes in children with suspected auditory processing disorders (APD), often absent or elevated, particularly in the crossed configuration. Meneguello et al. (2001) found elevated reflexes in 62% of the APD population. Thomas, McMurry and Pillsbury

(1985) suggested abnormal reflex thresholds in 32% of children with language delay, learning disability and who were suspected of APD but did not find any correlation between acoustic reflex abnormalities and children of suspected APD. Despite of the high incidences of reflex threshold abnormalities in children with suspected APD, measurements of reflex threshold are not typically included as diagnostic indicators in the assessment of auditory processing. In order to improve the accuracy of reflex threshold testing in the assessment of children with auditory processing disorders, normative data from children is preferable to that from adults as age-effects have sometimes been reported. As well, different norms for crossed and uncrossed reflexes should be used as thresholds for uncrossed reflexes are most often lower than for crossed reflexes in adult listeners (Fria, LeBlanc, Kristensen & Alberti, 1975; Gelfand, 2005; Jerger, Hayes, Anthony & Mauldin, 1978; Moller, 1961, 1962). However, developmental differences in crossed and uncrossed thresholds are unknown.

The morphology and functional characteristics of the conductive mechanism mature from birth to puberty (Abdala & Keefe, 2012; Obake, Tanaka, Hamada, Miura & Funai, 1988). Both ear canal volume and static compliance are smaller in children than in adults (Abdala & Keefe, 2012; Barlow et al., 1988; Jerger et al., 1978; Obake et al., 1988) and could influence the measurement and interpretation of reflex thresholds when comparing results between children and adults.

2.1.1 Real ear correction and reflex thresholds

Real ear corrections for differences in ear canal volume are common in many measures of hearing in children. When evaluating behavioral threshold or measuring hearing aid gain these corrections are nearly universally recommend (American Academy of Audiology [AAA], 2013). However, similar corrections have not been applied to reflex threshold measurements. Calibration of the stimulus used to elicit reflex thresholds is typically completed using a 2 cc coupler (Grason-Stadler, 2005; Interacoustics, 2011). It is known that sounds with similar intensities can result in different sound pressure levels (SPL) in ear canals with different volumes (Martin, 2003). It is likely that the reflex activator presented at a fixed intensity level result in a higher SPL in the ear canal with a smaller volume than in an ear with a larger volume. This could result in erroneous measurements of reflex thresholds in individuals with ear canal volume smaller than 2 cc such as children. While it is well accepted that real ear to coupler differences (RECD) in individuals with a small ear canal volume show larger RECD values and vice versa (Barlow et al., 1988; Feigin, Kopun, Stelmachowicz & Gorga, 1989; Martin, Westwood & Bamford, 1996), there has been no systematic investigation into the influence of real ear correction on reflex threshold measurements.

2.1.2 Static compliance and reflex thresholds

Age-related differences in static compliance could also impact estimates of children's acoustic reflex thresholds. Static compliance represents an estimate of the ease with which sound energy flows through the middle ear. Static compliance values are often lower in children than in adults (Jerger et al., 1972; Obake, et al., 1979). Near threshold, the reflex causes only a small change in the compliance of the middle ear. Smaller static compliance values could possibly make it difficult to measure this very small change. At higher stimulus levels the contraction of the stapedius muscle is stronger resulting in a larger change in compliance that may be easier to measure. This measurement parameter, which may vary developmentally, could lead to a higher estimate of reflex thresholds in children.

Wilson (1979) examined the impact of static compliance on acoustic reflex thresholds in normal hearing adults. He reported a low correlation between crossed thresholds and static compliance. But the participants in his study had histories of negative middle ear pressure which could have influenced measurements of reflex thresholds and static compliance and only crossed thresholds were measured. Correlating crossed reflex thresholds with static compliance of the measurement ear rather than the stimulus ear may have contributed to the lower correlation.

2.2 Study aims

The aim of this study was to replicate previous studies showing elevated reflex thresholds in children with suspected APD and to compare their crossed and uncrossed threshold estimates to those from typically developing children and normal hearing adults. Because ear canal volume and static compliance have shown developmental effects and because these factors could affect the measurements of reflex thresholds the second aim of this study was to examine the effect of real ear corrections for stimulus levels on thresholds and the relationship between static compliance and threshold estimates in both adults and children.

2.3 Study 1: Reflex Threshold Estimates in Crossed and Uncrossed Pathways for Normal Hearing Adults, Typically Developing Children and Children with Suspected Auditory Processing Disorder.

2.3.1 Methods

2.3.1.1 Participants

Participants in this study included 20 normal hearing adults (18-30 years of age), 28 typically developing children (7 to 15 years of age) and 66 children (aged 7 to 15 years) suspected of having an auditory processing disorder. The children suspected of having an auditory processing disorder were referred to the Child Hearing Research Laboratory by caregivers, teachers, parents, or physicians for an auditory processing assessment. All participants had normal otoscopic examination, normal hearing thresholds (American Speech-Language-Hearing Association [ASHA], 2005a), normal middle function (ASHA, 1988) and no history of neurologic disorder.

Children referred for the evaluation of suspected APD underwent a behavioral assessment that included the Staggered Spondaic Word test (Katz, 1998), the Pitch Pattern Sequence test (Pinheiro, 1977), the Words in Ipsilateral Competition test (Ivey, 1969, 1987) and two custom tests of signal feature encoding that evaluated frequency discrimination and gap detection in an adaptive 3-alternative forced-choice procedure designed to track the 70.7% correct threshold level. As suggested by ASHA (2005b), children who performed at least 2 standard deviations below age expectations on at least 2 of these tests were classified as APD. Those that did not meet the criterion but who reported listening difficulties were classified as clinical non-APD (Allen & Allan, 2014). Forty two of the children were therefore classified as APD and 24 as clinical non-APD.

2.3.1.2 Instrumentation

Otoscopic examination was conducted using a hand-held Welch Allyn otoscope. Pure tone audiometry and the auditory processing evaluation were administered using a Grason Stadler 61 (GSI 61) diagnostic audiometer and a JVC XL Z32 CD player. A GSI Tympstar Middle Ear Analyzer version 2 was used to evaluate middle ear function and obtain reflex thresholds. It was professionally calibrated for probe tone frequency, probe tone level, compliance, stimulus intensity level, volume and pressure according to American National Standard Institute [ANSI] S 3.39 (1987) standard.

2.3.1.3 Procedure

All impedance and reflex measurements were obtained with a 226 Hz probe tone. A proper hermetic seal was sustained during the testing. Crossed and uncrossed reflex thresholds were obtained using 500, 1000 and 2000 Hz pure-tone activator stimuli. For both conditions, reflex threshold measurements were made in 5 dB steps. A reflex amplitude of 0.02 ml or more was considered as the criteria for threshold estimation. Reflex measures were made twice at the same stimulus level in order to validate the threshold estimates. For the statistical analyses reported in this study, the Greenhouse-Geisser corrected values are reported whenever the assumption of sphericity was violated.

2.3.2 Results

Reflexes were absent in 3 typically developing, 6 APD and 4 clinical non-APD children in one or more measurement conditions. Therefore they were not included in the statistical analysis. Repeated measures analysis of variance (RM-ANOVA) showed no effect of stimulus ear on reflex thresholds [F (1, 100) = 1.575, p = 0.212], therefore data from right and left ear were averaged for each individual at each frequency and condition combination. Figure 2.1 shows the mean and standard error of reflex thresholds measured at 500, 1000 and 2000 Hz for the uncrossed and crossed conditions in all groups averaged across ears. Error bars show ±1 standard error. Thresholds in crossed and uncrossed conditions are shown by the open and filled symbols, respectively.

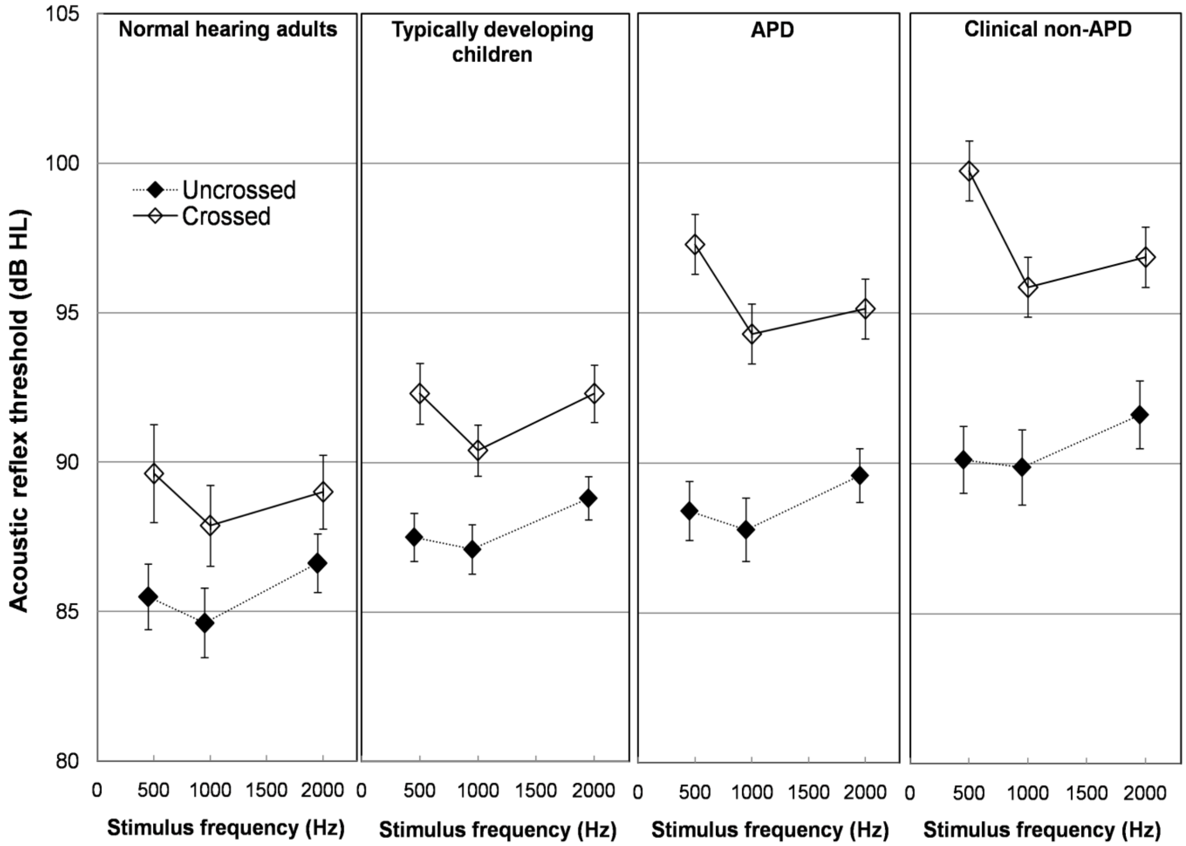

Figure 2.1: Mean of crossed and uncrossed reflex thresholds at 500, 1000 and 2000 Hz in normal hearing adults, typically developing children, APD and clinical non-APD averaged for right and left ears. Uncrossed and crossed reflex thresholds are represented with filled and open diamonds respectively. Error bars show ±1 standard error**.**

Overall, reflex thresholds were higher in crossed than in uncrossed conditions [F (1, 97) = 204.945, p < 0.001]. Consistent with previous reports (Allen & Allan, 2014), thresholds also varied across groups [F (3, 97) = 9.470, p < 0.001] and there was a significant group by condition interaction [F (3, 97) = 7.500, p < 0.001]. As can be seen in Figure 2.1 there was a tendency for higher thresholds and a larger crossed-uncrossed difference in the two groups of clinical children when compared to the adults and typically developing children. To better visualize the group-condition interaction differences between the crossed and uncrossed reflex thresholds (D-ART) were calculated. The mean and standard error of these differences (D-ART) at 500, 1000 and 2000 Hz are shown in Figure 2.2 for each group.

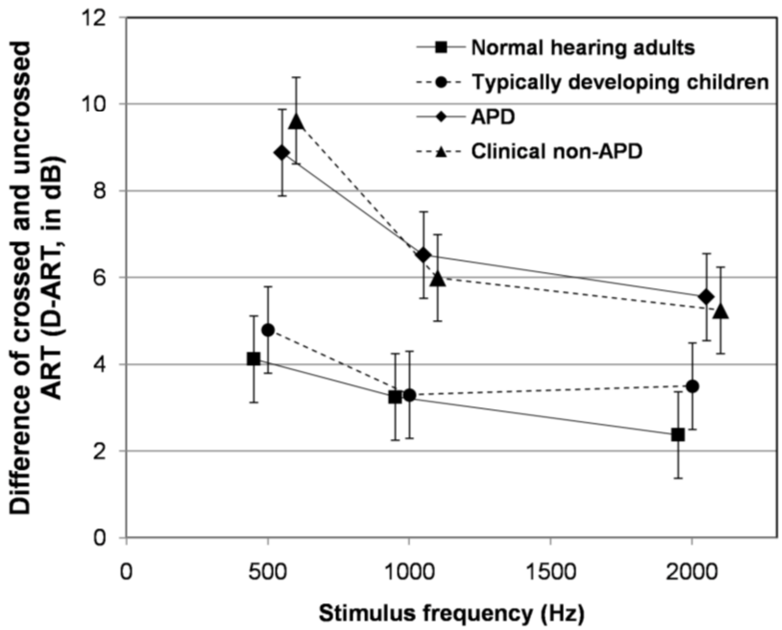

Figure 2.2: Mean of differences between crossed and uncrossed ART (D-ART) at 500, 1000 Hz and 2000 Hz (averaged for right and left ears). Squares, circles, diamonds and triangles represent normal hearing adults, typically developing children, APD and clinical non-APD, respectively. Error bars show $\pm$1 standard error.

A Bonferroni corrected post hoc t-test confirmed that typically developing children and normal hearing adults had similar D-ARTs (p = 1.000). Normal hearing adults had smaller D-ARTs in comparison to both clinical groups of children, [APD (p = 0.002) and clinical non-ADP (p = 0.009)]. Typically developing children also showed significantly different D-ARTs in comparison to the APD ($p = 0.007$) and clinical non-APD ($p = 0.030$) groups. There were no significant differences between the 2 clinical groups of children ($p = 1.000$). These results indicate that, in comparison to the uncrossed reflex thresholds, the crossed reflex thresholds were elevated to the greatest degree in the clinical groups of children.

There was a significant effect of stimulus frequency on the reflex thresholds [$F (1.725, 167.282) = 18.452$, $p < 0.001$] and a significant interaction between stimulus frequency and condition [$F (1.837, 178.224) = 25.339$, $p < 0.001$]. In the crossed condition, thresholds at 1000 Hz were significantly lower than those at 500 Hz ($p < 0.001$) or 2000 Hz ($p = 0.001$) and thresholds at 500 Hz were higher than 2000 Hz ($p = 0.009$). In the uncrossed condition, 500 and 1000 Hz had similar thresholds ($p = 0.131$) but significantly higher reflex thresholds were recorded at 2000 Hz when compared to 500 ($p = 0.001$) and 2000 Hz ($p < 0.001$).

2.3.3 Discussion

Crossed and uncrossed reflex thresholds were measured in normal hearing adults, typically developing children and children with suspected APD. The latter group of children included those who received a diagnosis of APD based upon a battery of clinically accepted behavioral tests (APD) and those who did not (clinical non-APD). For the participants in this study, there was no right-left ear difference on reflex thresholds which is consistent with previous reports (Osterhammel & Osterhammel, 1979; Wilson et al., 1981). Crossed reflex thresholds were always higher than the uncrossed thresholds and the effect was greatest in the children from the clinical groups. There were no differences between reflex thresholds recorded from typically developing children and those from normal hearing adults. Reflex thresholds differed between typical developing children and the clinical groups of children, especially for the crossed condition.

Reflex thresholds differed on the basis of stimulus frequency but the effect varied according to condition. This is consistent with reports from Gelfand (1984) who, in summarizing the findings from several studies reported that the effect of stimulus frequency on the reflex thresholds was not consistent.

Jerger et al. (1972), Jerger et al. (1978) and Osterhammel and Osterhammel (1979) suggested that children (aged 7 to 15 years) have higher reflex thresholds in comparison to adults. In the present study there was a tendency towards slightly higher thresholds in the typically developing children when compared to the adults but no statistically significant differences were found. Further, these results showed that a higher level of stimulation is required to activate the acoustic reflex in the crossed condition than in the uncrossed condition, consistent with previous reports (Fria et al., 1975; Gelfand, 2005; Jerger et al., 1978; Moller, 1962).

The primary goal of this study was to examine group related differences. Consistent with predictions and previous findings (Allen & Allan, 2014; Meneguello et al., 2001; Thomas et al., 1985). The children in the clinical groups had higher reflex thresholds when compared to normal hearing adults and typically developing children and showed greater differences between crossed and uncrossed thresholds. This suggests greater abnormalities in crossed reflex thresholds in children with clinical reports of listening difficulties.

The acoustic reflex is thought to increase speech intelligibility in noise by attenuating low frequency acoustic information (Aiken, Andrus, Bance & Phillips, 2013; Borg, 1968; Borg & Zakrisson, 1974; Colletti, Fiorino, Verlato & Carner, 1992; De Andrade et al., 2011; Dorman, Lindholm, Hannley & Leek, 1986; Simmons, 1964). Elevated reflexes in children with suspected APD may contribute to their most commonly reported problem of difficulty understanding speech in noise. Compared to typically developing children, reflexes in clinical groups of children may only be activated at higher noise levels and therefore the benefits of reflex activation may be limited. Greater reflex abnormalities were found to be associated with crossed pathways in the clinical population but the relative importance of crossed and uncrossed acoustic reflex pathways and their activation in speech perception is not well understood.

Children who were diagnosed with APD had numerically higher reflex thresholds compared to typically developing children but the differences were significant only in the crossed condition. The clinical non-APD group had both crossed and uncrossed reflex thresholds that were significantly different from typically developing children. These findings in clinical non-APD children may reflect an inability of behavioral tests to identify auditory processing disorders that originate due to auditory brainstem dysfunction.

2.4 Study 2: Effect of Real Ear Correction and Static Compliance on Uncrossed Acoustic Reflex Thresholds in Normal Hearing Children and Adults

Study 1 suggested that reflex thresholds tended to be slightly higher in children when compared to adults but stimulus values were not adjusted for potential differences in ear canal volume or static compliance. The effects of ear canal volume could be predicted to produce erroneous stimulus levels when calibration does not consider the smaller volume of the child's ear and thus potentially produce higher SPL in the ear. Similarly, the higher impedance of the child's middle ear could make it more difficult to measure a small change resulting from activation of the acoustic reflex and thus give an erroneous threshold measurement. In this study, both effects of ear canal volume and static compliance on acoustic reflex thresholds were measured in typically developing children and normal hearing adults.

2.4.1 Methods

2.4.1.1 Participants

Data were collected from the right ear of 28 normal hearing adults (aged 18 to 30 years) and 30 children who were typically developing (aged 7 to 15 years)**.** All participants had normal otoscopic examination, normal hearing thresholds (ASHA, 2005a), normal middle function (ASHA, 1988) and no history of neurologic disorder.

2.4.1.2 Procedure

2.4.1.2.1 Measurement of reflex thresholds, static compliance and ear canal volume:

Reflex thresholds, ear canal volume, static compliance and RECD values were measured using the TITAN (Interacoustic, 2011) middle ear measurement system. The TITAN was professionally calibrated for stimulus intensity level, volume and pressure according to American National Standard Institute [ANSI] S3.39 (1987) standard. Uncrossed reflex thresholds were measured at 500, 1000 and 2000 Hz for all participants. Reflex thresholds were measured using a 1 dB step size. The reflex thresholds were measured in dB HL and then converted to dB SPL using the Interacoustic standard reference equivalent threshold sound pressure level value for 500, 1000 and 2000 Hz (Interacoustic, 2011). Reflex amplitude of 0.02 ml or more was considered as the criteria for establishing reflex thresholds with each threshold validated by repeating the measure at the presumed threshold level at least once. The automatic gain control on the TITAN was turned off. A proper hermetic seal was maintained during the measurements.

2.4.1.2.2 Measurement of RECD

RECD measurements were obtained using the TITAN probe check function from the otoacoustic emissions test suite. Clicks with a flat spectrum from 226 to 8000 Hz were presented at an intensity level of 95 peSPL (approximately 60 dB SPL) and were measured in both a 2 cc coupler and the ear canal. Figure 2.3 shows an example of probe check measurements obtained in a 0.87cc ear canal and a

2 cc coupler. The continuous and broken lines represent the probe measurements in the ear canal and 2 cc coupler, respectively. Sound intensity levels in the coupler and ear canals at 500, 1000 and 2000 Hz were used to calculate real ear SPL at the stimulus frequencies.

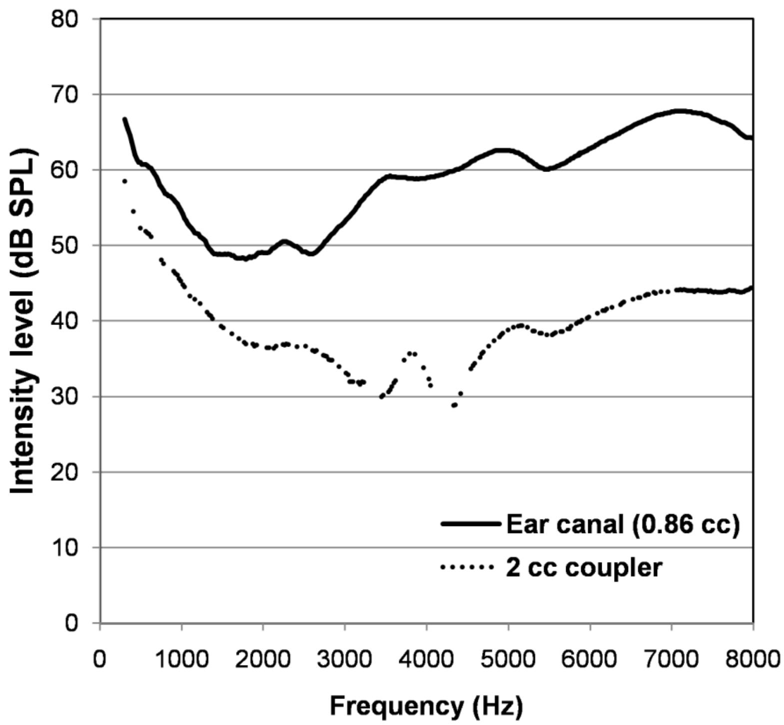

Figure 2.3: Example of a probe check measurement in a child's ear canal with an ear canal volume of 0.87 cc and in a 2 cc coupler. The continuous and broken lines represent the probe measurements in the ear canal and 2 cc coupler, respectively.

Ear canal measurements were made at the level of the probe. The intensity level measured at the probe for 500, 1000 and 2000 Hz is considered to well approximate the intensity level measured at the tympanic membrane (Caldwell, Souza & Tremblay, 2006; Gilman & Dirks, 1986; Interacoustics, 2011; Siegel, 1994). For this reason the distance of the probe from the tympanic membrane was not considered to be a significant factor in the measurements. Also, measurements in the ear canal were made with the same probe placement used for estimating reflex thresholds. This procedure ensured that the distance between the probe and tympanic membrane was identical while making the RECD and the reflex thresholds measurements. An example of the measurements obtained to estimate RECD at 500, 1000 and 2000 Hz in one participant with an ear canal volume of 0.87 cc is shown in Figure 2.4. Stars and plus signs represent the sound intensity levels measured in the 2 cc coupler and in the participant's ear canal, respectively. RECD was then calculated at 500, 1000 and 2000 Hz as the difference in the sound intensity level measured in the 2 cc coupler and participant's ear canal. These values were used in correcting reflex thresholds at the respective frequencies.

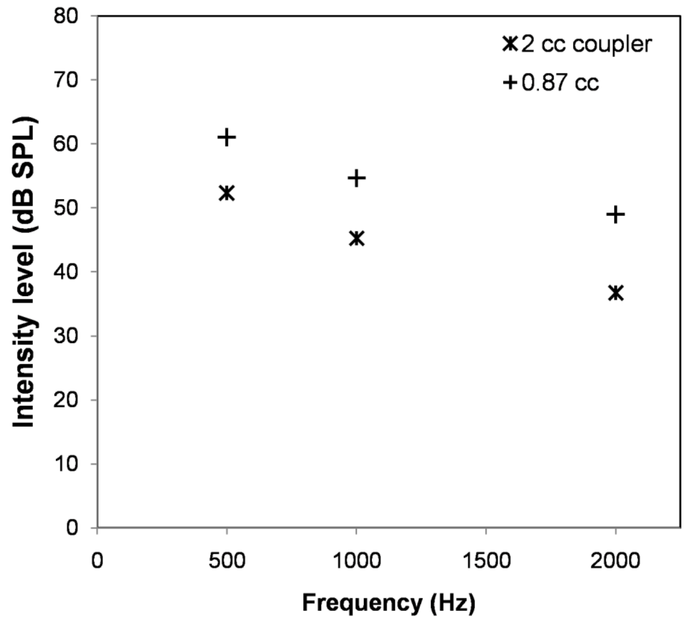

Figure 2.4: Example of measurements used to estimate RECD at 500, 1000 and 2000 Hz in a participant with an ear canal volume of 0.087 cc. Stars and plus signs represent the sound intensity levels measured in the 2 cc coupler and in the participant's ear canal, respectively.

2.4.2 Results

2.4.2.1 Real ear correction and reflex thresholds

Figure 2.5 shows the mean and standard error of RECD values in typically developing children and normal hearing adults. The mean and standard error of reflex thresholds corrected for volume (Corrected reflex thresholds) and the reflex thresholds measured without real ear correction (Uncorrected reflex thresholds) in typically developing children and normal hearing adults are shown in Figure 2.6.

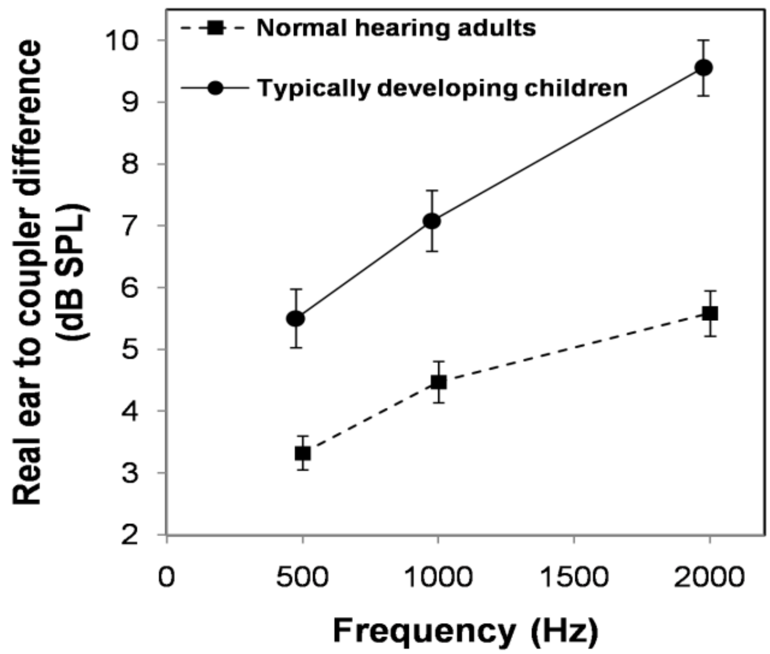

Figure 2.5: Mean of RECD values at 500, 1000 and 2000 Hz. Circles and squares represent typically developing children and normal hearing adults, respectively. Error bars show ±1 standard error.

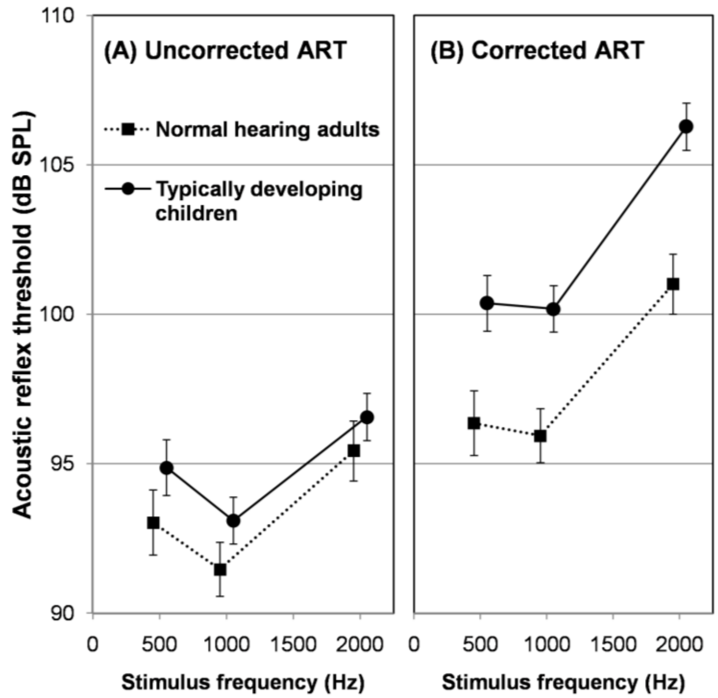

Figure 2.6: Mean of uncorrected (A) and corrected (B) acoustic reflex thresholds at 500, 1000 and 2000 Hz for the typically developing children and normal hearing adults. Typically developing children and normal hearing adults are shown by the circles and squares symbols, respectively. Error bars show ±1 standard error.

An independent T- test showed significantly [t (56) = 6.371, p < 0.001)] smaller ear canal volumes in typically developing children (mean = 0.8573 cc, standard deviation = 0.13) in comparison to the normal hearing adults (mean = 1.16 cc, standard deviation = 0.23). A RM-ANOVA showed a significant effect of real ear correction on reflex thresholds in both typically developing children and normal hearing adults [F (2, 56) = 515.714, p = 0.000]. Reflex thresholds corrected for volume differences were greater than the non-corrected reflex thresholds in both groups (Figure 2.6). Real ear correction had a significant interaction with group which was further analyzed using a pair wise comparison. It was found that corrected reflex thresholds were significantly higher in the typically developing children as compared to the normal hearing adults ($p = 0.002$). The two groups had similar reflex thresholds when they were not corrected for volume ($p = 0.207$). This suggests that the effect of real ear correction on reflex thresholds was greatest in typically developing children (Figure 2.6).

The effect of stimulus frequency on reflex thresholds, was found to be significant [$F (1.711, 95.812) = 60.956$, $p < 0.001$], as was the interaction between volume correction and stimulus frequency [$F (1.659, 92.898) = 81.707$, $p < 0.001$)]. Pair-wise analyses were conducted to investigate the volume correction-stimulus frequency interaction and it was discovered that the uncorrected reflex thresholds were significantly different at 500, 1000 and 2000 Hz ($p < 0.001$ for each pair). Uncorrected reflex thresholds had the lowest values at 1000 Hz followed by 500 Hz and 2000 Hz. When reflex thresholds were corrected for volume, the threshold values were similar at 500 and 1000 Hz ($p = 1.000$) but were significantly higher at 2000 Hz when compared to 500 Hz ($p < 0.001$) and 1000 Hz ($p < 0.001$). This analysis also suggested that the effect of the correction for volume was greatest for reflex thresholds at 2000 Hz followed by 1000 and then 500 Hz (Figure 2.6).

2.4.2.2 Static Compliance and reflex thresholds

The Pearson Correlation Coefficient was used to examine the relationship between static compliance and corrected/uncorrected reflex thresholds. A statistically significant correlation between static compliance and reflex thresholds was found in normal hearing adults for corrected and uncorrected reflex thresholds at 500, 1000 and 2000 Hz (Table 2.1). Lower reflex thresholds were measured in the ears with higher static compliance (Figure 2.7). There was no statistically significant relationship observed between static compliance and reflex thresholds in typically developing children in both corrected and uncorrected reflex thresholds conditions (Table 2.1). Figure 2.7 shows corrected acoustic reflex thresholds plotted against static compliance. Adults and children are shown in top and bottom panel, respectively

	Uncorrected reflex thresholds			Corrected reflex thresholds		
Groups	500 Hz	1000 Hz	2000 Hz	500 Hz	1000 Hz	2000 Hz
Typically developing children	0.333 (p=0.072)	0.301 (p=0.106)	0.343 (p=0.064)	0.088 (p=0.644)	0.046 (p=0.810)	0.261 (p=0.163)
Normal hearing adults	0.769** (p<0.001)	0.749** (p<0.001)	0.624** (p<0.001)	0.815** (p<0.001)	0.719** (p<0.001)	0.616** (p<0.001)

**Correlation Significant at 1% level

Table 2.1: Pearson Correlation Coefficient for static compliance and reflex thresholds (Uncorrected and corrected for ear canal volume differences).

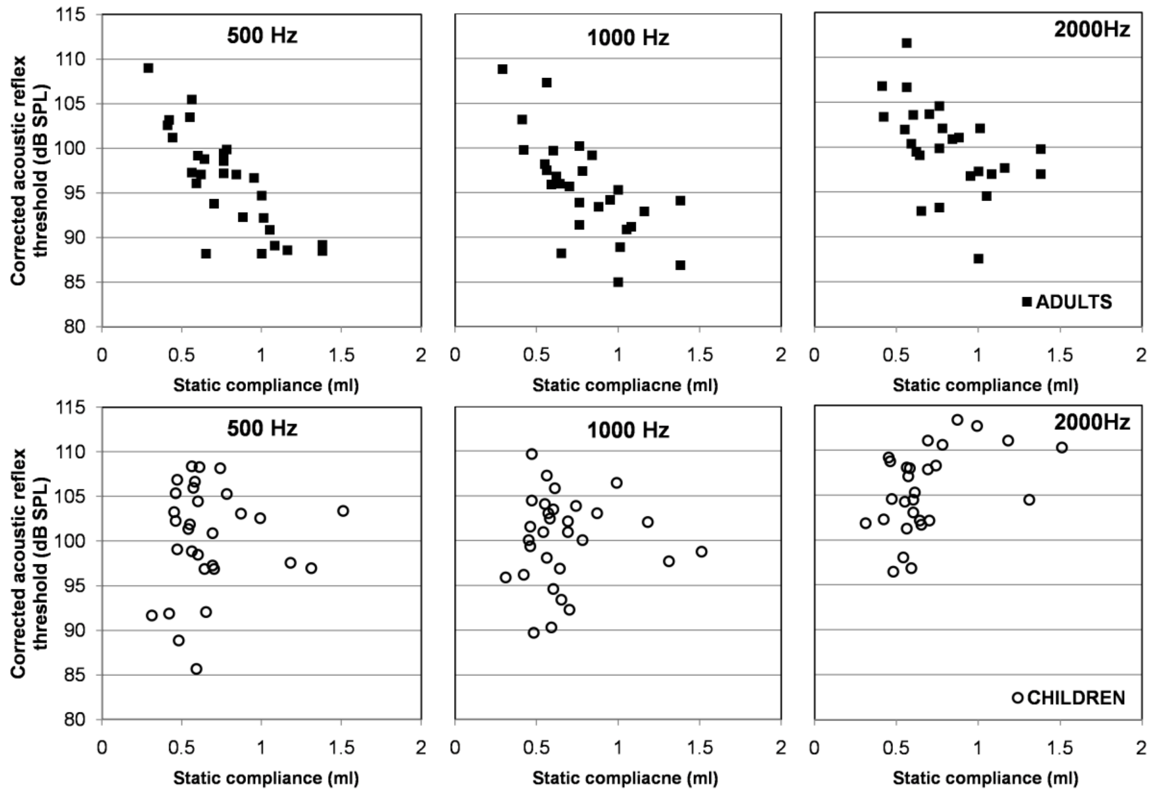

Figure 2.7: Corrected acoustic reflex thresholds plotted against static compliance. Adults and children are shown in top and bottom panel, respectively.

2.4.3 Discussion

In this experiment ear canal volume, static compliance, acoustic reflex threshold and real ear to coupler difference values were measured in typically developing children and normal hearing adults. Similar to the findings of Jerger et al. (1978) and Barlow et al. (1988), significantly smaller ear canal volumes were found in typically developing children as compared to the normal hearing adults. RECD values in typically developing children and normal hearing adults were consistent with previously reported values (Bagatto, Scollie, Seewald, Moodie & Hoover, 2002; Sachs & Burkhard, 1972).

The effect of real ear correction on reflex thresholds at 500, 1000 and 2000 Hz varied because of the distinct RECD values at 500, 1000 and 2000 Hz. The reflex thresholds measured at 2000 Hz were most affected by the volume correction followed by 1000 Hz and then 500 Hz. The reflex thresholds for 500 Hz signals were initially measured at significantly higher levels than the reflexes for the 1000 Hz signals but after applying a volume correction these reflex thresholds were no longer different. The 2000 Hz reflex thresholds were significantly higher than those measured with 500 and 1000 Hz signals regardless of whether a correction for individual volume differences was applied but the extent of differences in the thresholds was increased. These results suggest that the frequency effect in reflex thresholds is mainly related to measurement issues. Clinical middle ear analyzers often have optional corrections for ear canal volume differences but they generally apply the same correction across all frequencies and canal volumes, largely to limit potentially dangerous SPLs in the smaller ears of young listeners. As seen in this study, RECD values were different at different frequencies in the ear canal and for this reason ear canal volume correction should be frequency and individual ear specific.

Typically developing children and normal hearing adults had statistically similar reflex thresholds when measured without correcting for volume differences. When reflex thresholds in both the groups were corrected for ear canal volume using RECD values, a significant difference emerges between typically developing children and normal hearing adults.

In Study 1 of this chapter, typically developing children had reflex thresholds that were statistically similar to the normal hearing adults although there was a tendency for children to have higher reflex thresholds. When a frequency specific real ear correction was applied to the reflex thresholds the two groups showed significantly different reflex thresholds. These findings suggest that real ear correction of reflex thresholds may impact the interpretation of thresholds measured in children. This highlights the clinical importance of ear canal volume correction in the measurement of all measures based on sound pressure levels in the ear canal.

Uncrossed reflex thresholds were found to have strong correlation with static compliance in normal hearing adults. This strong correlation showed that reflex thresholds in adults vary as a function of static compliance, such that low reflex thresholds are recorded in ears with a high static compliance and vice versa. Surprisingly, in typically developing children there was no correlation between uncrossed reflex thresholds and static compliance. As static compliance in children did not correlate with reflex thresholds it can be suggested that the elevated thresholds found in children may result from non-mechanical factors, perhaps relating to neural maturation. Previously, Gelfand (1984) described several factors such as noisiness and fidgetiness in children, instrument sensitivity, measurement procedure and chances of undetected conductive problems in children in addition to static compliance that could possibly be responsible for the difference in reflex thresholds between children and adults. But a recent study, Skoe, Keizman, Anderson and Kraus (2013) showed a developmental trend in auditory brainstem maturation measured by the ABR that continued until 11 years of age. Therefore it is possible that elevated reflex thresholds in children could be due to neural development in the auditory brainstem.

2.5 General conclusions of this chapter

Children with suspected APD showed elevated reflex thresholds as compared to typically developing children and normal hearing adults. Interestingly, reflex abnormalities were greater in the clinical group of children who were not diagnosed as APD based on the behavioral test battery in comparison to those who received the diagnosis. These acoustic reflex findings demonstrate the inability of the behavioral test measures, commonly used in the assessment of APD, to identify all of the factors possibly contributing to the experience of listening difficulty. Functionally elevated reflex thresholds would suggest that children with suspected APD require higher stimulus levels for reflex activation and therefore the benefits from reflex activation in speech perception in the presence of noise may be limited.

Typically developing children differed from normal hearing adults when reflex thresholds were corrected for ear canal volume differences. The two groups also differed in the relationship between static compliance values and reflex thresholds. Clinically, these results highlight the necessity to correct reflex thresholds for individual ear canal volume differences especially when interpreting reflex thresholds in children. It also showed the importance to develop children specific reflex norms and to compare reflex measures in the pediatric clinical population to that of typically developing children rather than to normal hearing adults.

2.6 Reference

Abdala, C., & Keefe, D. H. (2012). Morphological and functional ear development. In L. A. Werner, R. R Fay & A. N. Popper (Eds.), *Human Auditory Development* (pp. 19-59). New York: Springer.

Aiken, S. J., Andrus, J. N., Bance, M., & Phillips, D. P. (2013). Acoustic Stapedius Reflex Function in Man Revisited. *Ear and hearing*, *34*(4), e38-e51..

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. & Allan, C. (2014). Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

American Academy of Audiology [AAA]. (2010). American Academy of Audiology Clinical Practice Guidelines: Pediatric Amplification. Retrieved from http:// www.audiology.org/resources/

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

American National Standards Institue [ANSI] (1987) Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance). ANSI S3.39-1987. New York: American National Standards Institute

Anderson, H., Barr, B., & Wedenberg, E. (1970). Early diagnosis of VIIIth-nerve tumours by acoustic reflex tests. *Acta Oto-Laryngologica Supplement*, *263*, 232-237.

Bagatto, M. P., Scollie, S. D., Seewald, R. C., Moodie, K. S., & Hoover, B. M. (2002). Real-ear-to-coupler difference predictions as a function of age for two coupling procedures. *Journal of the American Academy of Audiology*, *13*(8), 407-415.

Barlow, N. L. N., Auslander, M. C., Rines, D., & Stelmachowicz, P. G. (1988). Probe-tube microphone measures in hearing-impaired children and adults. *Ear and hearing*, *9*(5), 243-247.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *Acta Oto-laryngologica, 66*, 461-472.

Borg, E., & Zakrisson, J. E. (1974). Stapedius reflex and monaural masking. *Acta oto-laryngologica*, *78*(1-6), 155-161.

Caldwell, M., Souza, P. E., & Tremblay, K. L. (2006). Effect of probe tube insertion depth on spectral measures of speech. *Trends in amplification*, *10*(3), 145-154.

Colletti, V., Fiorino, F.G., Verlato, G. & Carner, M. (1992). Acoustic reflex in frequency selectivity: Brain stem auditory evoked response and speech discrimination. In J. Katz, N.A. Stecker & D. Henderson (Eds.). *Central Auditory Processing: A Transdisciplinary View* (pp. 39-46). St. Louis, MO: Mosby - Year Book, Incorporated.

De Andrade, K.C.L., Camboim, E.D., Soares, I.D.A., Peixoto, M.V.D.S., Neto, S.C., Menezes, P.D.L. (2011). The importance of acoustic reflex for communication. *American Journal of Otolaryngology – Head and Neck Medicine and Surgery, 32*, 221-227.

Dorman, F., Lindholm, J. M., Hannley, M. T., & Leek, M. R. (1987). Vowel intelligibility in the absence of the acoustic reflex : Performance-intensity characteristics. *The Journal of the Acoustical Society of America81(2),* 562–564.

Feigin, J. A., Kopun, J. G., Stelmachowicz, P. G., & Gorga, M. P. (1989). Probe tube microphone measures of ear canal sound pressure levels in infants and children. *Ear and Hearing*, *10 (4)*, 254-58.

Ferguson, M., Smith, P., Lutman, M., Mason, S., Coles, R., & Gibbin, K. (1996). Efficiency of tests used to screen for cerebellopontine angle tumours: a prospective study. *British Journal of Audiology*, 30(3), 159-176.

Fria, T., LeBlanc, J., Kristensen, R., & Alberti, P. W. (1974). Ipsilateral acoustic reflex stimulation in normal and sensorineural impaired ears: a preliminary report. *Canadian journal of otolaryngology*, *4*(4), 695-703.

Gelfand, S. A. (1984). The contralateral acoustic reflex threshold. In: S. Silman (Ed.), *The acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Gelfand, S.A. (2005). The acoustic reflex. In J. Katz (Ed.), *Handbook of clinical audiology: Fifth Edition* (pp: 205-232). Baltimore, MD: Lippincott Williams & Wilkins.

Gilman, S., & Dirks, D. D. (1986). Acoustics of ear canal measurement of eardrum SPL in simulators. *The Journal of the Acoustical Society of America*,*80*(3), 783-793.

Grason-Stadlor (2005). *GSI tympstar version 2: Middle ear analyzer-Reference instruction manual.*

Hall, J.W. (1982). Quantification of the relationship between crossed and uncrossed acoustic reflex amplitudes. *Ear and Hearing*, 3, 296-300.

Interacoustics (2011). *TITAN-Instruction for use.*

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.

Jerger, J., Hayes, D., Anthony, L. & Mauldin, L. (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Monographs in Contemporary Audiology*, *1*, 1-20.

Jerger, S., & Jerger, J. (1977). Diagnostic value of crossed vs uncrossed acoustic reflexes: Eighth nerve and brain stem disorders. *Archives of Otolaryngology*, *103*(8), 445-453.

Jerger, J., Jerger, S., & Mauldin, L. (1972). Studies in Impedance Audiometry: I. Normal and sensorineural ears. *Archives of Otolaryngolology*, *96*, 513-523.

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

Mangham, C., Lindeman, R., & Dawson, W. (1980). Stapedius reflex quantification in acoustic tumor patients. *Laryngoscope*, *90*, 242-250.

Martin, H. C., Westwood, G.F.S. & Bamford, J.M. (1996). Rear ear to coupler differences in children having otitis media with effusion. *British Journal of Audiology*, *30*, 71-78.

Martin, R. L. (2003). Deep canal fittings: Acoustics and comfort. *The Hearing Journal*, *56*(10), 52.

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian journal of otorhinolaryngology*, *67* (7), 830-835.

Moller, A. R. (1961). Bilateral contraction of the tympanic muscles in man examined by measuring acoustic impedance-change. *The Annals of otology, rhinology, and laryngology*, *70*, 735.

Moller, A.R. (1962). Acoustic reflex in man. *The Journal of the Acoustical Society of America*, *34*, 1524-1534.

Moore, J. K., & Linthicum Jr, F. H. (2007). The human auditory system: a timeline of development. *International journal of audiology*, *46*(9), 460-478.

Okabe, K., Tanaka, S., Hamada, H., Miura, T., & Funai, H. (1988). Acoustic impedance measurement on normal ears of children. *Journal of the Acoustical Society of Japan (E)*, *9*(6), 287-294.

Osterhammel, D., & Osterhammel, P. (1979). Age and sex variationsfor the normal stapedial reflex thresholds and tympanometric compliance values. *Scandinavian Audiology*, *8*, 153-158.

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

Prasher, D., & Cohen, M. (1993). Effectiveness of acoustic reflex threshold criteria in the diagnosis of retrocochlear pathology. *Scandinavian audiology*,*22*(1), 11-18.

Sachs, R. M., & Burkhard, M. D. (1972). Insert earphone pressure response in real ears and couplers. *The Journal of the Acoustical Society of America*,*52*(1A), 183-183.

Salamy, A. (1984). Maturation of the auditory brainstem response from birth through early childhood. *Journal of Clinical Neurophysiology*, *1*(3), 293-329.

Siegel, J. H. (1994). Ear-canal standing waves and high-frequency sound calibration using otoacoustic emission probes. *The Journal of the Acoustical Society of America*, *95*(5), 2589-2597.

Silman, S., & Gelfand, S. A. (1979). The effect of age on stapedius reflex growth function in normal and pathological ears. *The Journal of the Acoustical Society of America*, *65*(S1), S10-S10.

Silman, S. & Gelfand, S.A. (1981). Effect of sensorineural hearing loss on the stapedius reflex growth function in the elderly. *The Journal of the Acoustical Society of America, 69*, 1099-1106.

Simmons, F. B. (1964). Perceptual theories of middle ear muscle function. *The Annals of otology, rhinology, and laryngology*, *73*, 724-739.

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2013). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex*, bht311.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope*, *95*, 811-817.

Thomsen, J., & Terkildsen, K. (1975). Audiological findings in 125 cases of acoustic neuromas. *Acta Oto-Laryngologica, 80,* 353-361. *Acta Oto-Laryngologica*, *96,* 353-361.

Wiley, T. L., Oviatt, D. L., & Block, M. G. (1987). Acoustic-immittance measures in normal ears. *Journal of Speech, Language, and Hearing Research*, *30*(2), 161-170.

Wilson, R. H. (1979). Factors influencing the acoustic-immittance characteristics of the acoustic reflex. *Journal of Speech, Language, and Hearing Research*, *22*(3), 480-499.

Wilson, R.H. (1981). The effects of aging on the magnitude of the acoustic reflex. *Journal of Speech and Hearing Research*, *24*, 406-414.

Wilson, R.H., Shanks, J.E. & Velde, T.M. (1981). Aural acoustic immittance measurements: Inter-aural differences. *Journal of Speech and Hearing Disorders*, *46*, 413-421.

Chapter 3

3 Crossed and Uncrossed Acoustic Reflex Growth Functions in Normal Hearing Adults, Typically Developing Children and Children with suspected Auditory Processing Disorder

3.1 Introduction

The acoustic reflex is an auditory system feedback mechanism in which the stapedius muscle contracts following sufficient acoustic stimulation (Liberman & Guinan, 1998). This contraction acts over a range of stimulus activator levels to modify input to the cochlea in a frequency selective manner by increasing middle ear impedance. Because it is strongest in response to high level stimulation it is believed to have a protective effect, limiting high level sounds entering the cochlea (Borg, Counter & Rosler, 1984). However, because its effect is frequency specific it likely plays a role in improving the perception of speech in noise (Aiken, Andrus, Bance & Phillips, 2013; Borg & Zakrisson, 1974; Colletti, Fiorino, Verlato & Carner, 1992; De Andrade et al., 2011; Dorman, Cedar, Hannley & Leek, 1986).

The acoustic reflex is often used in audiology to evaluate auditory peripheral and brainstem function. Measurement of acoustic reflex thresholds (Anderson, Barr & Wedenberg, 1970; Johnson, 1977), reflex growth functions (Harrison, Silman & Silverman, 1989; Mangham, Lindeman & Dawson 1980; Silman, Popelka & Gelfand, 1978), reflex decay (Anderson et al., 1970;

Mangham et al., 1980; Olsen, Noffsinger & Kurdziel, 1975) and reflex latencies (Clemis & Sarno, 1980; Hess, 1979; Mangham et al., 1980) have been shown to be important in assessing neural integrity. A less commonly used measure is the evaluation of the strength of the reflex response with changes in stimulus activator level (Harrison et al., 1989; Mangham & Lindeman, 1980; Silman et al., 1978). In individuals with normal reflex pathways, the amplitude of the reflex grows with increases in the intensity of the activator stimulus from threshold to a point at which it reaches saturation. The function describing changes in reflex amplitude with stimulus intensity is described as the Acoustic Reflex Growth Function (ARGF; Silman, 1984).

The ARGF may provide a useful measure of neural integrity at the level of the brainstem that may be more sensitive to pathology than the more commonly measured reflex threshold. Borg (1973) showed in animal models that severing some brainstem tracts resulted in depression of the reflex growth function, often with no or only minimal impact on the reflex threshold. In humans, shallower reflex growth has been shown in patients with cerebellar (Harrison et al., 1989) and eighth nerve tumors (Mangham & Lindeman, 1980). The shallower growth was reasoned to reflect a decrement in neural activity caused by the auditory nerve compression due to the tumor. Because the acoustic reflex likely plays a role in facilitating hearing in noise, it may have functional as well as neuro-diagnostic value in the assessment of individuals reporting difficulty hearing in noise. One such group includes those with suspected auditory processing disorders (APD) for whom difficulty hearing in noise is a common complaint

(American-Speech-Language-Hearing-Association [ASHA], 2005a). However, to date, growth functions have not been measured in these children.

Some studies have reported abnormal reflex thresholds in APD. Meneguello et al. (2001) reported absent or abnormally elevated acoustic reflex in nearly two-thirds of the individuals with APD whom they tested. But Thomas, McMurry and Pillsbury (1985) reported that only one-third of their subjects showed abnormal reflex thresholds. More recently, Allen and Allan (2014) examined acoustic reflex thresholds in crossed and uncrossed configurations in children with suspected APD. They reported abnormal reflexes in approximately half of the children tested, often absent, particularly when measured in the crossed configuration. While suggesting that a large number of children with listening difficulties and suspected APD may have reflex abnormalities that potentially could contribute to their difficulty hearing in noise, these studies used only the presence or absence of the acoustic reflex or the reflex threshold as the criteria to define abnormalities. Given the suggestion from animal models (Borg, 1973) that reflex thresholds may be less sensitive to dysfunction of the reflex pathway than the ARGF, the potential importance of the acoustic reflex in facilitating speech perception in noise, and the knowledge that magnitude changes with stimulus level, this study investigated the ARGF in children with reported listening difficulties who were suspected of having an APD. Both crossed and uncrossed pathways were evaluated and compared. Normal hearing children and adults were included as controls.

3.2 Method

3.2.1 Participants

Participants included 37 children (7 to 15 years of age) referred to the Child Hearing Research Laboratory at the National Centre for Audiology for APD evaluation because of listening and/or academic problems thought to arise from difficulty hearing or understanding auditory information. Sixteen normal hearing adults (18-30 years of age) and 17 typically developing children (7 to 15 years of age) participated as controls. All participants had normal otoscopic examination, normal hearing thresholds (ASHA, 2005b), normal middle function (ASHA, 1988) and no history of neurologic disorder.

Children referred with suspicion of APD received a behavioral assessment that included the Staggered Spondaic Word test (Katz, 1998), the Pitch Pattern Sequence Test (Pinheiro, 1977), the Words in Ipsilateral Competition test (Ivey, 1969, 1987) and two custom tests of frequency discrimination and gap detection that used an adaptive three-alternative forced-choice procedure designed to track 70% correct threshold levels. As suggested by ASHA (2005a), children who performed at least 2 standard deviations below age expectations on at least 2 of these tests were classified as APD. Previous work (Allen & Allan, 2014) has suggested that many children who report listening difficulties but do not meet a criterion for APD diagnosis using a strictly behavioral test battery may show objective indicators of auditory pathology in the brainstem pathways. Therefore, all children who were referred for assessment of listening difficulties were included in this study. Those who did not meet the behavioral criterion for APD diagnosis were classified as clinical non-APD to reflect that they were part of a clinical group but not categorized as APD based on behavioral test standards. Twenty three of the children were therefore classified as APD and 14 as clinical non-APD group.

3.2.2 Procedure

A Grason-Stadler GSI TympStar Middle Ear Analyzer version 2 was used to measure acoustic reflexes. The instrument was professionally calibrated for probe tone frequency, probe tone level, compliance, volume and pressure according to American National Standards Institute [ANSI] S3.39 (1987) standard. These calibration values are used by the GSI Tympstar software to ensure reliable measures of reflex amplitude.

Reflex growth functions were obtained for crossed and uncrossed conditions using 500, 1000 and 2000 Hz pure-tones as activator stimuli. All impedance and reflex measurements were obtained with a 226 Hz probe tone. A proper hermetic seal was sustained during the testing. Acoustic reflex thresholds were estimated in 5 dB steps using ascending run. A reflex amplitude of 0.02 ml or greater, measured twice, was used as the criteria for establishing an acoustic reflex threshold (dB HL). Reflex amplitude was measured at four stimulus levels: acoustic reflex threshold and 5, 10 and 15 dB above threshold. If participants felt uncomfortable with the stimulus level, measurement was restricted to not exceed comfort levels. Limitations of the instrument/transducers occasionally restricted the stimulus level for specific frequencies and this also reduced the number of steps in the growth function for some listeners. Obtaining reflex amplitudes for at least 3 stimulus levels was the minimum inclusion criteria for any condition.

Reflex amplitude measurements can be influenced by additive or tympanic membrane artifacts especially when measuring uncrossed reflexes. The chances of additive artifacts in reflex measurement are higher when the reflex eliciting stimulus and probe tone frequencies are close (Danaher & Pickett, 1974; Green & Margolis, 1984; Hall, 1982; Kunov, 1977; Newall, Royall & Lightfoot, 1978; Niswander & Ruth, 1976). This interaction was avoided by using a low probe tone frequency, 226 Hz (Green & Margolis, 1984) and stimulus frequency that is higher than 500 Hz (Niswander & Ruth, 1976). Reflex artifacts can also be avoided by using instruments with efficient filters (Danaher & Pickett, 1974; Newall et al., 1978; Niswander & Ruth, 1976). The efficiency of the filters can be assessed by placing the probe in a hard wall cavity and then stimulating it as in the uncrossed condition with different stimulus intensities and frequencies (Kunov, 1977). Absence of any response will indicate higher efficiency of the filter to separate probe tone and stimuli. A similar assessment was performed and verified for 500, 1000 and 2000 Hz pure-tone elicitors at different intensities using a 2 cc coupler. In addition, visual inspection was done during reflex measurement to rule out tympanic membrane artifacts or a combination of tympanic membrane and additive artifacts.

Large inter-subject variability is possible in ARGF slope measures due to differences in static compliance across individuals (Silman, 1984; Sprague, Wiley & Gelfand, 1981). For a given stimulus level, a larger reflex amplitude may be measured in ears with larger static compliance (Silman & Gelfand, 1981; Wilson, 1981). The decibel transformation method suggested by Silman and Gelfand (1981) was adopted to normalize reflex amplitudes for differences in static compliance. This method involves expressing the reflex amplitude in terms of the change in acoustic compliance caused by the activation of the reflex relative to the compliance measured in the absence of the reflex and converting this acoustic compliance change into decibels. The formula for this decibel transformation is given as

$$\text{Acoustic compliance change in dB} = 20 \log \frac{\Delta Y}{Y}$$

where ΔY is the change in acoustic compliance, calculated by subtracting reflex amplitude from static compliance (Y).

A total of 12 reflex growth functions (2 ears X 2 conditions X 3 stimulus frequencies) were measured in each participant. For each condition and stimulus frequency combination the slopes of the reflex growth functions were calculated by a linear fit between acoustic compliance change in dB and stimulus level (in dB SL with respect to ART).

3.3 Results

Absent and elevated thresholds (≥ 105 dB HL) were found in one or more measures in some participants from all the groups but, consistent with previous data (Allen & Allan, 2014) abnormalities were more frequent and more severe in the two clinical groups. There were no instances of absent reflexes in the normal hearing adults or typically developing children but elevated thresholds were found in 2 of the 16 adults and 3 of the 17 typically developing children. In the groups of children with clinical complaints,6 children from the APD and 7 children from the clinical non APD were found to have elevated, but not absent thresholds at one or more frequencies and 4 children from the APD and 3 children from the clinical non-APD groups had absent reflexes.

Slopes of the ARGFs were calculated from the 63 individuals with no absent reflexes (16 adults, 17 typically developing children, 19 children with an APD diagnosis and 11 clinically referred but non-APD). Goodness of fit was examined using R^2 values. Two normal hearing adults, 3 APD and 5 clinical non-APD had fits in one or more conditions for which the R^2 was ≤ 0.7, mostly occurring when there was no or extremely low growth of the reflex magnitude with changes in stimulus level.

Repeated measures analysis of variance (RM-ANOVA) was done to examine frequency, ear, condition and group effects. Greenhouse-Geisser corrected values are reported whenever the assumption of sphericity was violated. Figure 3.1 shows the mean and standard error of the slopes of the reflex growth functions in crossed and uncrossed conditions plotted separately for the four groups of participants. Slopes in the uncrossed and crossed conditions are shown by the filled and open symbols, respectively. Right and left ears are shown by the circles and diamonds, respectively. Negative slopes represent a decrease in static compliance with increase in reflex activator stimulus level. There were no significant slope differences between ears [F (1,

59) = 0.942, p = 0.336] and no significant differences for stimulus frequency [F (1.706, 100.659) = 0.080, p = 0.897]. Overall, the effect of group was not significant [F (3, 59) = 2.591, p = 0.061]. The effect of condition (crossed vs uncrossed) [F (1, 59) = 130.720, p < 0.001] and the condition by group interaction [F (3, 59) = 5.309, p = 0.003] were significant. Crossed slopes were shallower when compared to uncrossed slopes in all the groups but the effect was largest for children in the two clinical groups. When data from participants with functions showing an $R^2 \leq 0.7$ were excluded, the effects were unchanged (Ear [F (1, 49) = 3.324, p = 0.074], frequency [F (1.673, 81.997) = 0.171, p = 0.805], group [F (3, 49) = 1.616, p = 0.198], condition [F (1, 49) = 119.191, p < 0.001] and condition by group interaction [F (3, 49) = 5.121, p = 0.004]).

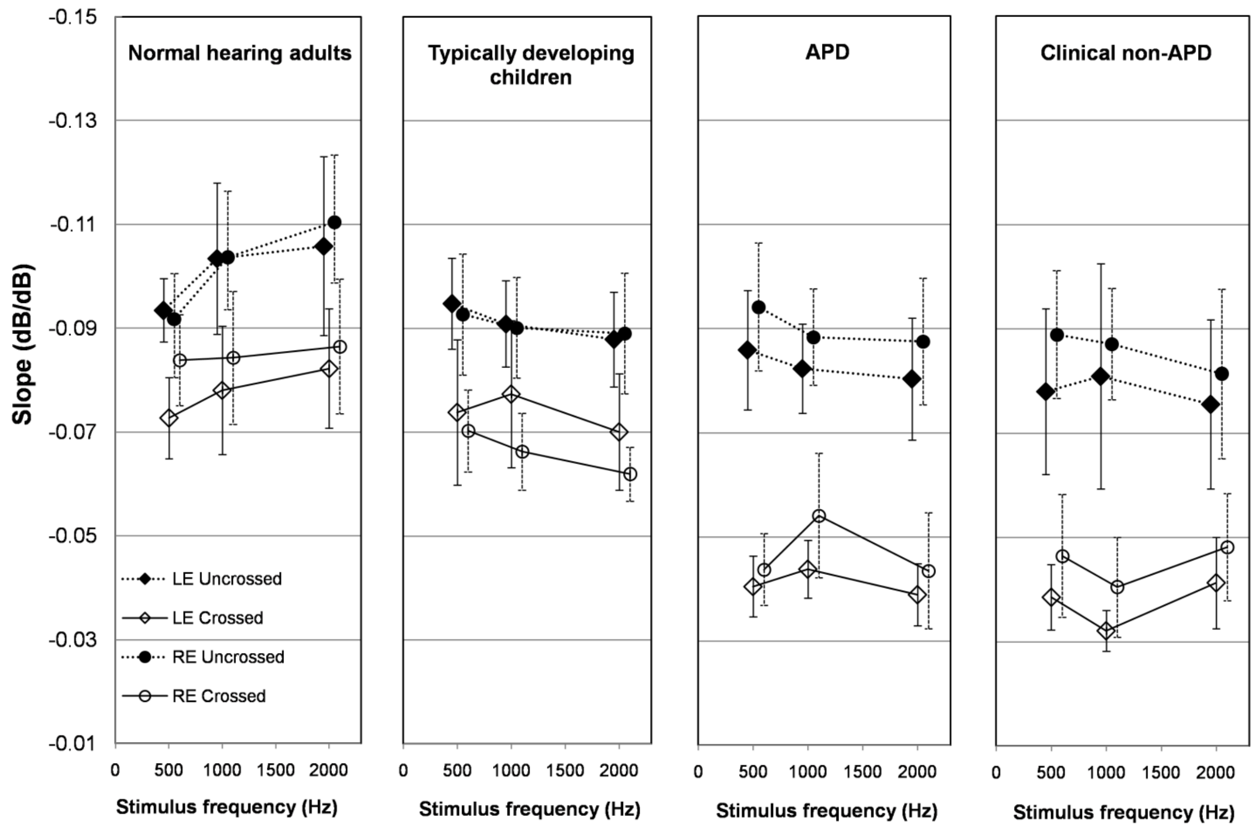

Figure 3.1: Mean slopes of the reflex growth functions at 500, 1000 and 2000 Hz. Separate panels show data from the adults, typically developing children, children with an APD diagnosis and clinically referred children who did not receive an APD diagnosis. Slopes in the uncrossed and crossed conditions are shown by the filled and open symbols, respectively. Right and left ears are shown by the circles and diamonds, respectively. Error bars show +1 standard error.

The group by condition interaction was examined by calculating the ratio of crossed/uncrossed slopes for each frequency and ear of each participant. Figure 3.2 shows the ratio of crossed/uncrossed ARGF slopes for individual participants. Open and filled symbols show data in the left and right ears, respectively. Data at 500, 1000 and 2000 Hz are shown by the diamonds, squares and circles, respectively. For comparison with adult data, dashed and dotted lines show 1 and 2 standard deviations with reference to adult ratios averaged across ear and frequency.

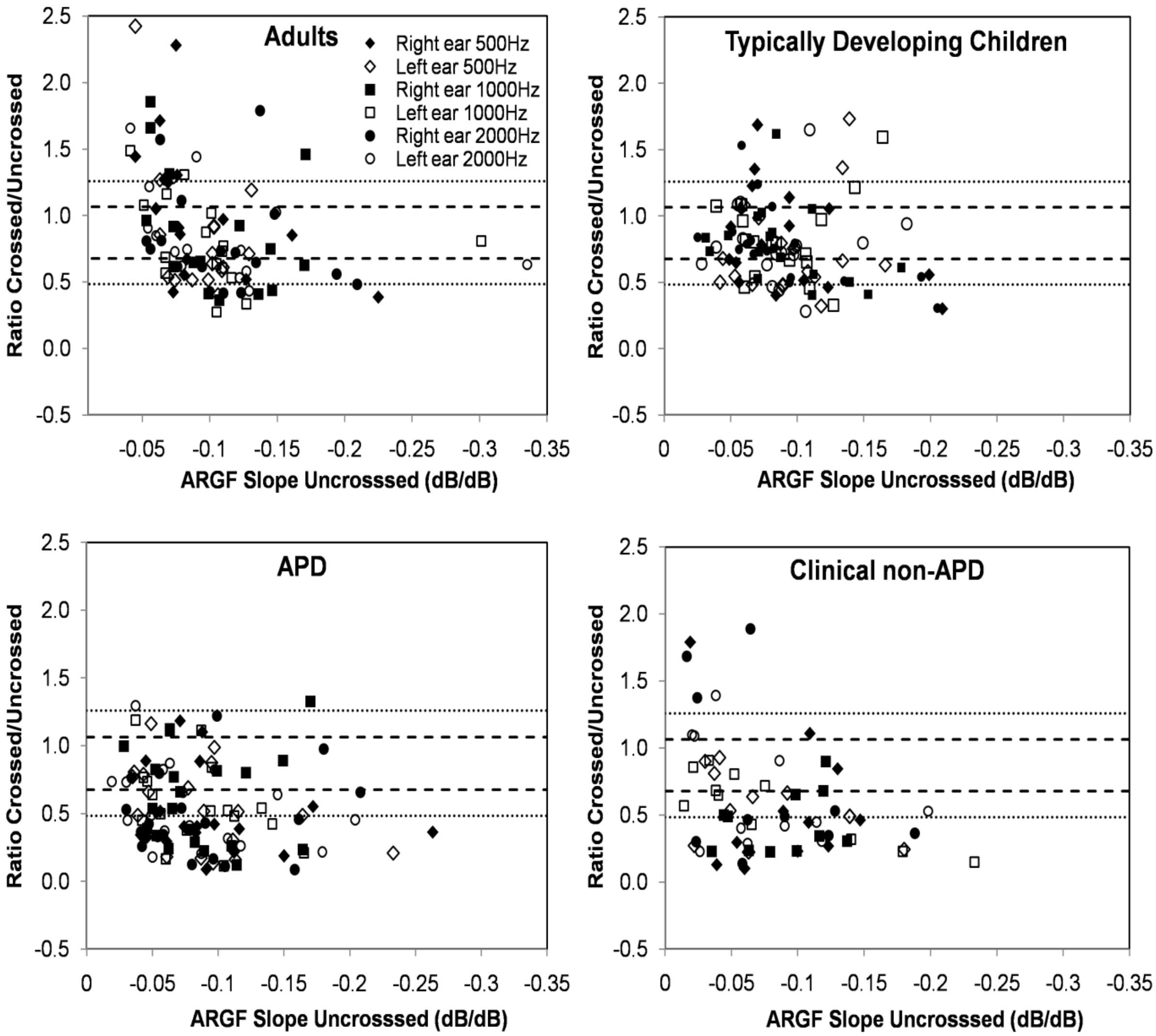

Figure 3.2: Ratio of crossed to uncrossed reflex growth function slopes plotted against the slope of the uncrossed reflex growth functions. Data from the normal hearing adults, typically developing children, APD and clinical non-APD are shown in separate panels. Each data point shows an individual ratio. Data measured at 500, 1000 or 2000 Hz are shown by the diamonds, squares and circles, respectively. Filled and open symbols show data in right and left ears, respectively.

RM-ANOVA on slope ratios revealed no significant effect of ear [$F(1, 59) = 0.036$, $p = 0.851$] or frequency [$F(2, 118) = 0.322$, $p = 0.725$] but there was a significant effect of group [$F(3, 59) = 15.312$, $p < 0.001$]. Results of Bonferroni post hoc tests showed that normal hearing adults and typically developing children had similar crossed/uncrossed slope ratios ($p = 1.000$). Normal hearing adults had significantly greater ratios than did children in the APD ($p < 0.001$) and clinical non-APD ($p < 0.001$) groups. Typically developing children were also found to have greater ratios in comparison to APD ($p < 0.001$) and clinical non-APD ($p = 0.014$) children. Slope ratios were not different when data from children in the APD and clinical non-APD groups were compared ($p = 1.000$). Unlike the typically developing children, most of the children from clinical groups (APD and clinical non-APD) had crossed/uncrossed ARGF slope ratios that were more than 1 standard deviation smaller than those of the adults and several had ratios that were more than 2 standard deviations smaller.

3.4 Discussion

This study measured acoustic reflex growth functions in crossed and uncrossed configurations in normal hearing adults, typically developing children and children with listening difficulties. The latter group of clinically referred children was further divided into two groups, those who received a diagnosis of APD based upon a battery of clinically accepted behavioral tests (APD) and those who did not (clinical non-APD). Results showed no significant slope differences between ears or frequency, consistent with previously reported data from adults (Sprague et al., 1981; Wilson, Shanks & Velde, 1981). Slopes tended to be significantly shallower in the crossed than uncrossed conditions and the difference was significantly larger in the clinical groups of children than in the typically developing children or adults.

Slope differences in crossed and uncrossed conditions are consistent with reports from Moller (1961, 1962 a, b) and Jerger, Hayes, Anthony and Mauldin (1978). The anatomy of the crossed and uncrossed reflex pathways has been described in the literature but little has been reported that may account for differences in the relative strength of the two pathways. Crossed stimulation has previously been reported to require higher level stimulation for activation of the reflex, i.e. higher crossed than uncrossed thresholds (Gelfand, 2005) and to produce lower amplitude responses (Hall, 1982). These observations may suggest weaker crossed pathways compared to uncrossed.

Comparison of data from typically developing children and adults suggested adult-like reflex growth in school-aged children. There have been no previous studies that reported reflex growth in children. Age effects have been reported in older individuals as compared to younger adults (Silman & Gelfand, 1981; Thompson, Sills, Recke & Bui, 1980; Wilson, 1981).

In contrast to typically developing children, children in the two clinical groups showed many differences compared to adults. Of the 37 children referred to this study with listening difficulties, elevated reflex thresholds were found in 20 children. Seven had absent reflexes and 13 others had elevated only reflexes in one or more condition. This finding is consistent with that of reflex abnormalities reported in children with suspected APD by Allen and Allan (2014). Acoustic reflex growth functions from children in clinical groups were shallower than those measured in adults and typically developing children, especially in the crossed condition. Crossed and uncrossed differences were most clearly seen in the growth ratios comparing crossed to uncrossed growth. With this comparison 24 of the 30 children in the clinical groups (19 from the APD and 11 from the clinical non-APD groups) had ratios more than 1 standard deviation below adult values and 10 children (7 APD and 3 clinical non APD) were more than 2 standard deviations below.

Reflex growth measurements are affected by individual differences in static compliance (Silman & Gelfand, 1981; Sprague et al., 1981). But this likely did not contribute to group differences seen in this study as the raw data was normalized for individual differences in static compliance. Further, using crossed/uncrossed slope ratios minimized the effect of static compliance on the differences. Differences between groups were therefore more likely to reflect differences in the neural pathways underlying the reflexes.

Moller (1961) suggested that neural activity at the level of the superior olivary complex underlies growth of acoustic reflex amplitude with stimulus activation level. Reduced growth of reflex amplitudes has been documented in patients with dysfunction in various neural nuclei of the reflex pathway (auditory nerve, cochlear nucleus and stapedius motor neuron). Reduced reflex growth in children with auditory processing difficulties may suggest dysfunction in the neural pathways of the brainstem.

Irrespective of the stimulus frequency eliciting the acoustic reflex , the effect of middle ear muscle activation is to increase impedance of the middle ear system. The impact on sound transmission due to muscle contraction is frequency specific, attenuating low frequency transmission more than high (Borg, 1968). It is believed that the reflex protects the inner ear from damage due to high level sound and improves speech perception, especially in noise. The protective role of the acoustic reflex is likely limited because the duration between the stimulus onset and the activation of the reflex is most often over 100 msec (Gorga & Stelmachowicz, 1983; Hung & Dallos, 1972; Qiu & Stucker, 1998) making it less effective for preventing damage from impulse noise or stimulus onsets. Its role in improving speech intelligibility in noise by attenuating low frequency information may be more significant (Borg, 1968; Simmons, 1964). Several studies have supported its importance in speech perception tasks. Aiken et al. (2013) highlighted the role of acoustic reflex in preventing upward spread of masking at moderate levels. De Andrade et al. (2011) and Colletti et al. (1992) described the importance of acoustic reflex in speech discrimination and frequency selectivity, respectively. Dorman et al. (1986) reported improved vowel recognition in normal hearing listeners when their acoustic reflexes were activated. Borg and Zakrisson (1974) showed that ears with acute stapedius muscle paralysis had greater masking compared to ears with reflexes present at stimulus levels above reflex thresholds, though masking was the same in both ears below reflex threshold. A possible implication of shallow reflex growth may be that the individual would not obtain as much benefit in noise, or with increased signal level, as would an individual with a steeper growth function. The high incidence of reduced reflex growth and absent or elevated reflexes in children with suspected APD may be related to their most common reported problem of difficulty understanding speech in noise. However, abnormalities are most often present in the crossed reflex pathway and there has been no investigation into the relative importance of crossed and uncrossed pathways on speech perception.

Clinical importance of measuring reflex growth function in children with suspected APD is shown in Figure 3.3. Slope ratios were averaged across the non-significant factors of stimulus frequency and ear for each participant and plotted against uncrossed slopes which were also averaged across ear and frequency. Twenty-four of the 30 children from the clinical groups [19 APD (open diamonds) and 11 clinical non-APD (open triangles)] showed ratios of crossed/uncrossed ARGF slopes less than 0.68 [more than 1 standard deviation below the adult data (filled squares)]. Ten fell more than 2 standard deviations below adult data (< 0.48). In contrast, none of the typically developing children (filled circles) showed averaged ratios less than 2 standard deviation below the adult data. Eleven of the clinical children with reduced ratio had normal reflex thresholds which suggest greater sensitivity of reflex growth function in assessing neural integrity in children with suspected APD.

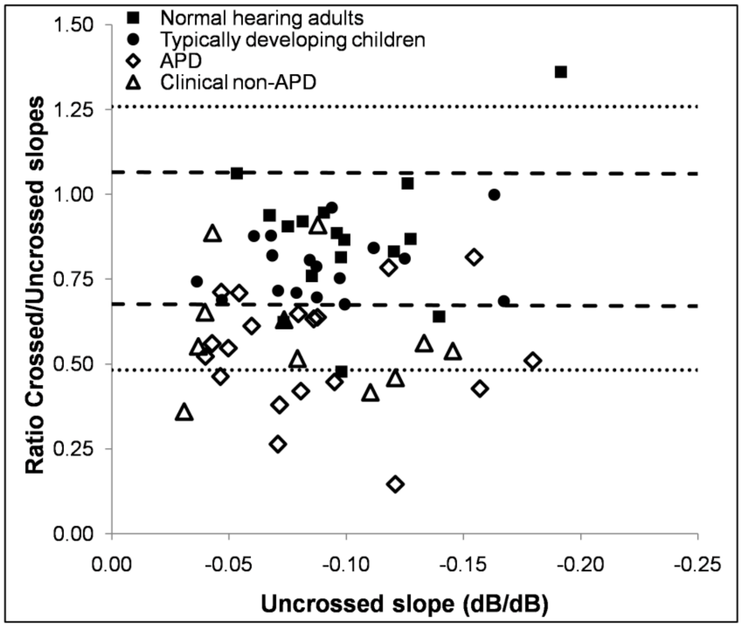

Figure 3.3: Average ratio of crossed to uncrossed reflex growth function slopes for each participant plotted against the average slope of the uncrossed growth function. Ratios were averaged for each individual across ears and frequencies. Data from the normal hearing adults and typically developing children are shown by the filled squares and circles, respectively. Data from children in the clinical groups, APD and non-APD are shown by open diamonds and triangles, respectively.

3.5 Conclusion

This study showed frequent abnormalities in reflex growth functions in children reporting listening difficulties and seeking APD assessment with no significant differences in children receiving or not receiving an APD diagnosis based upon an entirely behavioral test battery. Many of the children were diagnosed to have normal auditory processing but showed similarly reduced reflex growths as seen in those who did receive an APD diagnosis. These findings highlight the limitations of behavioral APD tests in detecting auditory deficits that may underlie the reported listening difficulties similar to previous reports (Allen & Allan, 2014).

The relationship between the functional role of acoustic reflexes in speech in noise perception and the high incidence of reflex abnormalities and poor speech in noise perception in children with suspected APD may suggest the importance of detailed acoustic reflex testing in assessing this population.

3.6 References

Aiken, S. J., Andrus, J. N., Bance, M., & Phillips, D. P. (2013). Acoustic Stapedius Reflex Function in Man Revisited. *Ear and hearing*, *34*(4), e38-e51.

Allen, P. & Allan, C. (2014). Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

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. (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 National Standards Institue [ANSI] (1987) Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance). ANSI S3.39-1987. New York: American National Standards Institute.

Anderson, H., Barr, B. & Wedenberg, E. (1970). Early diagnosis of VIIIth-nerve tumours by acoustic reflex tests. *Acta Oto-Laryngologica Supplement, 263,* 232-237.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *Acta Oto-laryngologica, 66*, 461-472.

Borg, E. (1973). On the neuronal organization of the acoustic middle ear reflex. A physiological and anatomical study. *Brain Research*, *49*, 101-123.

Borg, E. Counter, S. A. & Rosler, G. (1984). Theories of middle ear muscle function. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Borg, E., & Zakrisson, J. E. (1974). Stapedius reflex and monaural masking. *Acta oto-laryngologica*, *78*(1-6), 155-161.

Clemis, J.D. & Sarno, C.N. (1980). The acoustic reflex latency test: Clinical application. *Laryngoscope*, 90, 601-611.

Colletti, V., Fiorino, F.G., Verlato, G. & Carner, M. (1992). Acoustic reflex in frequency selectivity: Brain stem auditory evoked response and speech discrimination. In J. Katz, N.A. Stecker & D. Henderson (Eds.). *Central Auditory Processing: A Transdisciplinary View* (pp. 39-46). St. Louis, MO: Mosby - Year Book, Incorporated.

Danaher, E. M., & Pickett, J. M. (1974). Notes on an artifact in measurement of the acoustic reflex. *Journal of Speech, Language, and Hearing Research*,*17*(3), 505-509.

De Andrade, K.C.L., Camboim, E.D., Soares, I.D.A., Peixoto, M.V.D.S., Neto, S.C., Menezes, P.D.L. (2011). The importance of acoustic reflex for communication. *American Journal of Otolaryngology – Head and Neck Medicine and Surgery, 32*, 221-227.

Gelfand, S.A. (2005). The acoustic reflex. In J. Katz (Ed.), *Handbook of clinical audiology: Fifth Edition* (pp: 205-232). Baltimore, MD: Lippincott Williams & Wilkins.

Gorga, M. P. & Stelmachowicz, P. G. (1983). Temporal characteristics of the acoustic reflex. *Audiology*, *22,* 120-127.

Green, K. W., & Margolis, R. H. (1984). The ipsilateral acoustic reflex. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Hall, J.W. (1982). Quantification of the relationship between crossed and uncrossed acoustic reflex amplitudes. Ear and Hearing, 3, 296-300.

Harrison, T., Silman, S. & Silverman, C.A. (1989). Contralateral acoustic reflex growth function in a patient with a cerebellar tumor: A case study. *Journal of Speech and Hearing Disorders, 54*, 505-509.

Hess, K. (1979). Stapedius reflex in multiple sclerosis. *Journal of Neurology, Neurosurgery & Psychiatry*, *42*(4), 331-337.

Hung, I. J. & Dallos, P. (1972). Study of the acoustic reflex in human beings. I. Dynamic characteristics. *The Journal of the Acoustical Society of America, 52 (4), 1972-80.*

Ivey, R. G. (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.

Jerger, J., Hayes, D., Anthony, L. & Mauldin, L. (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Monographs in Contemporary Audiology, 1*, 1-20.

Johnson, E.W. (1977). Auditory test results in 500 cases of acoustic neuroma. *Archives of Otolaryngology, 103*, 152-158.

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

Kunov, H. (1977). The "eardrum artifact" in ipsilateral reflex Measurements.*Scandinavian audiology*, *6*(3), 163-166.

Liberman, M. C., & Guinan, J. J. (1998). Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlear efferents. *Journal of Communication Disorders*, *31*(6), 471–82.

Mangham, C., Lindeman, R. & Dawson, W. (1980). Stapedius reflex quantification in acoustic tumor patients. *Laryngoscope, 90*, 242-250.

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian journal of otorhinolaryngology*, *67* (7), 830-835.

Moller, A. R. (1961). Bilateral contraction of the tympanic muscles in man examined by measuring acoustic impedance-change. *The Annals of otology, rhinology, and laryngology*, *70*, 735.

Moller, A.R. (1962a). The sensitivity of contraction of the tympanic muscles in man. *The Annals of Otology, Rhinonogy and Laryngology, 71*, 86-95.

Moller, A.R. (1962b). Acoustic reflex in man. *The Journal of the Acoustical Society of America, 34*, 1524-1534.

Newall, P., Royall, R. A., & Lightfoot, G. R. (1978). Some observations on the contralateral stapedial reflex artefact. *British journal of audiology*, *12*(3), 78-82.

Niswander, P. S., & Ruth, R. A. (1976). An artifact in acoustic reflex measurement: some further observations. *Ear and Hearing*, *1*(5), 209-214.

Olsen, W.O., Noffinger, D. & Kurdziel, S. (1975). Acoustic reflex and reflex decay. Occurrence in patients with cochlear and eighth nerve lesions. *Archives of Otolaryngology, 101*, 622-625.

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

Qiu, W.W. & Stucker, F.J. (1998). Characterization of acoustic reflex latency in normal-hearing subjects. *Scandinavian Audiology, 27*, 43-49.

Silman, S. (1984). Magnitude and growth of the acoustic reflex. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Silman, S. & Gelfand, S.A. (1981). Effect of sensorineural hearing loss on the stapedius reflex growth function in the elderly. *The Journal of the Acoustical Society of America, 69*, 1099-1106.

Silman, S., Popelka, G.R. & Gelfand, S.A. (1978). Effect of sensorineural hearing loss on acoustic stapedius reflex growth functions. *The Journal of the Acoustical Society of America, 64*, 1406-1411.

Sprague, B.H., Wiley, T.L. & Block, M.G. (1981). Dynamics of acoustic reflex growth. *Audiology, 20*, 15-40.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope, 95*, 811-817.

Thompson, D.J., Sills, J.A., Recke, K.S. & Bui, D.M. (1980). Acoustic reflex growth in the aging adult. *Journal of Speech and Hearing Research*, *23*, 405-418.

Wilson, R.H. (1981). The effects of aging on the magnitude of the acoustic reflex. *Journal of Speech and Hearing Research, 24*, 406-414.

Wilson, R.H., Shanks, J.E. & Velde, T.M. (1981). Aural acoustic immittance measurements: Inter-aural differences. *Journal of Speech and Hearing Disorders, 46*, 413-421.

Chapter 4

4 Time Course of the Acoustic Reflex in Normal Hearing Adults, Typically Developing Children and Children with Suspected Auditory Processing Disorders: Latency and Decay

4.1 Introduction

4.1.1 Acoustic reflex latency

Acoustic reflex latency describes the time course of the middle ear muscle contraction following stimulus onset. Bosatra, Russolo and Silverman (1984) defined reflex latency as the time between the a onset of reflex activator and the first change detected in the impedance of the middle ear as a result of the reflex. Both onset and offset latencies can be measured, but the reflex latency can be measured using different criteria. For example, onset latency, is measured as the time between stimulus onset and the point of certain change in impedance generally defined as the point of initial change (Clemis & Sarno, 1980; Hess, 1989; Mangham, Lindeman & Dawson, 1980; Qui & Stucker, 1998), the point where a 5% of the impedance change has occurred (Gorga & Stelmachowicz, 1983) or the point at which the reflex amplitude reaches 10% or 90% of its maximum amplitude (Borg, 1982; Qui & Stucker, 1998). Rise time has been defined as the time between the first and maximum change in impedance (Norris, Stelmachowicz, Bowling & Taylor, 1974), as the time between stimulus onset and a 50% change in impedance (Borg, 1982; Hess, 1989) or as the time between 10% and 90% of the maximum reflex amplitude (Liden, Nilsson, Laaskine, Roos & Miller, 1974; Qui & Stucker, 1998).

Similarly, offset latency is measured as the time between stimulus offset and the point where reflex amplitude falls to 5% or 95% of its maximum amplitude (Norris et al., 1974) or to the point where reflex amplitude falls 10% or 90% of its maximum amplitude (Qui & Stucker, 1998). Colleti (1974) and Qui and Stucker (1998) described the time from the point when the reflex amplitude decreases from 90% to 10% (of the maximum reflex amplitude) after stimulus offset as the fall time. Borg (1982) defined fall time between the end of the stimulus presentation and the point where the reflex decreased to 50% of the maximum reflex amplitude. Because of the different definitions of reflex latencies described in various studies, there are variations in the normative values for reflex latency across studies. As well, the temporal characteristics and sensitivity of different immitance instruments can affect reflex latencies (Bosatra et al., 1984; Gefand, 2005; Lilly, 1984; Qui & Stucker, 1998). It is therefore suggested that clinicians develop and use instrument specific norms for reflex latencies for clinical comparisons (Jerger, Oliver & Stach, 1986; Qui & Stucker, 1998).However, in general, most studies show typical onset latencies (10% change) around 115 msec, with amplitude reaching 90% of the maximum value around 235 msec and 90% and 10% offset latencies around 120 and 235 msec, respectively.

There are no guidelines suggested for clinically significant delays but reflex latencies have been measured in individuals with auditory nerve and auditory brainstem disorders. For example, Hess (1979) measured the onset latency (time between stimulus onset and first change in impedance) and rise time (which was described as the time between the stimulus onset and the point where reflex amplitude reaches 50% of its maximum amplitude) for crossed reflexes using a 1000 Hz pure-tone activator in patients with multiple sclerosis and normal hearing controls. One third of patients with multiple sclerosis were found to have delayed onset latency [Mean = 124.1 msec, standard deviation = 64.8] and rise time [Mean = 343.6 msec, standard deviation = 74.3] in comparison to normal hearing individuals (onset latency [Mean = 90.2 msec, standard deviation = 17.7] and rise time ([Mean = 201 msec, standard deviation = 36.5]). Delayed latencies were more frequent for rise time in patients with multiple sclerosis. Clemis and Sarno (1980) estimated onset reflex latencies (described as the time between stimulus onset and the first change in impedance) at 1000 and 2000 Hz in crossed and uncrossed condition in patients with eighth nerve tumors and in normal hearing individuals. With a 1000 Hz or 2000 Hz activator, reflex latencies in patients with eighth nerve tumors were prolonged by an average of 78.5 and 168.7 msec, respectively, in comparison to normal hearing individuals   Mangham, Lindeman and Dawson (1980) reported higher (approximately 200 msec) crossed reflex latency (described as the time between stimulus onset and first change in impedance) in the affected ear of patients with unilateral auditory nerve tumor in contrast to normal hearing individuals. Overall, reflex latencies measured in individuals with auditory nerve and auditory brainstem disorders showed delayed onset latencies. There has been no investigation of offset latencies in the assessment of auditory nerve or auditory brainstem disorders.

4.1.2 Acoustic reflex decay

The amplitude of the reflex grows to its maximum magnitude after the activator stimulus is presented but the reflex may undergo some adaptation and amplitude decreases if stimulation continues. The decrease in amplitude of the reflex when the activator stimulus is sustained for long durations is called reflex decay. Reflex adaptation and reflex fatigue are other terms used in literature to describe reflex decay.

Reflex decay can be estimated by measuring the time for a specified decrease in reflex amplitude, for example 50% decrease from its maximum amplitude (Gelfand, 2005; Wilson, Shanks & Lilly, 1984).Decay can also be measured in terms of the amount of decrease in reflex amplitude after a given period of time. Clinically, a decrease of reflex amplitude by 50% within 10 seconds of the stimulus onset is used as an indication of retrocochlear pathology (disorder of auditory nerve and auditory brainstem). Reflex decay is dependent on the type and/or frequency of the stimulus (Wilson et al., 1984). Normal hearing individuals typically show little decay for pure-tones below 1000 Hz during the first 30 seconds of stimulus presentation. In contrast the reflex reduces to 50% of its maximum amplitude within 15 seconds for pure-tones above 2000 Hz. Decay for broadband stimuli is similar to that of higher frequency pure-tones.

Like reflex latencies, reflex decay is also reported to be sensitive to auditory nerve and auditory brainstem dysfunctions. Anderson, Barr and Wedenberg (1970) measured the amount of reflex decay in patients with tumors of the auditory nerve or posterior fossa and normal hearing individuals. At 500 and 1000 Hz, where normal hearing individuals showed minimal decay, the reflex amplitude of tumor patients was halved within 3 seconds of stimulus presentation. At 2000 and 4000 Hz, normal hearing individuals showed a 50% decay in reflex amplitude at 14 and 7 seconds, respectively, while in patients with tumors time for 50% decay was reached within only 5 seconds. Similar reports showing rapid decay in patients with an acoustic nerve tumor were indicated in several other studies (Jerger, Harford, Clemis & Alford, 1974; Olsen, Stach & Kurdziel, 1981; Sanders, Josey & Glasscock, 1981; Sheehy & Inzer, 1976). In patients with multiple sclerosis, Anderson, Barr and Wedenberg (1969 as cited in: Wilson et al., 1974) found that a mean time for the reflex amplitude to decay by 50% was only 6.3 seconds. In summary, these studies indicate that individuals with auditory nerve and auditory brainstem dysfunctions are more prone to show rapid decay of reflex amplitude.

4.1.3 Children with suspected APD

Auditory brainstem dysfunction in children with suspected APD has been suggested in some previous studies. Sanches and Carvallo (2006) and Muchnik et al. (2004) reported that contralateral suppression of transient evoked otoacoustic emission in children with suspected APD was significantly reduced in comparison to normal hearing children. Banai and Kraus (2007), Gopal and

Kowalski (1999), Gopal and Pierel (1999) and Jisra (2001) showed poor morphology, prolonged latencies and reduced amplitude of the components of auditory brainstem response in children with suspected APD. Absent and elevated reflex thresholds have also been reported in children with suspected APD (Allen & Allan, 2007, 2014; Meneguello et al., 2001; Thomas, McMurry & Pillsbury, 1985). Previous work reported in this thesis (chapter 2 and 3) also showed absent or elevated reflex threshold and shallower growth of reflex functions in children with suspected APD when compared to normal hearing adults and typically developing children. Temporal characteristics of the acoustic reflex, including reflex latencies and reflex decay, have been found to be sensitive to dysfunction of the auditory brainstem and auditory nerve but have rarely been studied in children with suspected APD.

An important role of acoustic reflexes in facilitating speech perception in the presence of noise has been suggested (Aiken, Andrus, Bance & Phillips, 2013; Borg & Zakrisson, 1974; Colletti, Fiorino, Verlato & Carner, 1992; De Andrade et al., 2011; Dorman, Cedar, Hannley & Leek, 1986; Simmons, 1964). Abnormal reflex latencies and decay could limit the functional benefit of reflexes if reflex activation is delayed, if it decays excessively over time or if it fails to release promptly after stimulus cessation. Because difficulty with speech perception in the presence of noise is one of the most common reported difficulties in children with suspected APD, it is important to study all factors that may contribute to the ability. In this study reflex latencies and decay were measured in children with suspected APD and were compared with those of typically developing children and normal hearing adults. Detailed investigation of reflex latencies and decay may provide important information on the temporal characteristics of acoustic reflex in children with suspected APD and will further explore the possibilities of estimating auditory brainstem or auditory nerve disorders in children with suspected APD using these reflex measures.

4.2 Methods

4.2.1 Participants

Normal hearing adults (aged 18 to 30 years), typically developing children (aged 7 to 15 years) and children with suspected APD (aged 7 to 15 years) participated in this study. Children with suspected APD were referred to the Child Hearing Research Laboratory at the National Centre for Audiology by teachers, caregivers, parents and educational audiologists for APD evaluation because of listening and/or academic problems. All participants had normal otoscopic examination, normal hearing thresholds (American-Speech-Language-Hearing-Association [ASHA], 2005a), normal middle function (ASHA, 1988) and no history of neurologic disorder. Children with suspected APD were assessed with a behavioral test battery that included the Staggered Spondaic Word test (Katz, 1998), the Pitch Pattern Sequence Test (Pinheiro, 1977), the Words in Ipsilateral Competition test (Ivey, 1969, 1987) and two custom tests of frequency discrimination and gap detection that used an adaptive three-alternative forced-choice procedure designed to track the 70% correct threshold levels. In accordance with ASHA (2005b) recommendations, children who showed scores at least two standard deviations below age expectations on two measures were classified as APD. Those that did not meet the criterion but who were reported to experience listening difficulties were classified as clinical non-APD (Allen & Allan, 2014).

Reflex latencies were measured in 17 normal hearing adults, 19 typically developing children, 14 children with APD and 10 children classified as clinical non-APD. Participants for reflex decay measurements included 12 normal hearing adults, 12 typically developing children, 8 children with APD and 6 clinical referrals who were non-APD. While some adults and typically developing children took part in both the studies of latency and decay none of the children in the 2 clinical groups did so.

One typically developing child, 4 APD and 3 clinical non-APD who were originally recruited for the latency study had absent reflexes in one or more conditions and therefore testing was not completed with them. Similarly, decay was not measured in 2 APD children and 1 clinical non-APD child with absent reflexes.

4.2.2 Signals & measurements

4.2.2.1 Reflex latency

The GSI TympStar Middle Ear Analyzer version 2 was used to measure reflex latencies. The instrument was professionally calibrated for intensity levels, compliance, volume and pressure according to American National Standard Institute [ANSI] S 3.39 (1987) standard. Crossed and uncrossed reflex latencies were obtained for both the right and left ears using 500, 1000 and 2000 Hz pure-tone activator signals. Reflex latencies were measured at 10 dB SL (reference to the acoustic reflex threshold). Estimation of acoustic reflex thresholds was done using an ascending run and stimulus intensity was increased in 5 dB step. A reflex amplitude of 0.02 ml or greater was used as the criteria for establishing reflex threshold (dB HL). Acoustic reflex threshold was validated by repeating the measurement at least twice at the prescribed stimulus level. All measurements were obtained using a 220 Hz probe tone. A proper hermetic seal was maintained during the testing.

Reflex latencies were measured using the following parameters; 10% On Latency, 90% On Latency, 10% Off Latency, 90% Off Latency, rise time and fall time. Figure 4.1 shows the parameters used in the measurements of reflex latencies. The 10% and 90% On Latencies refers to the initial latency period from the onset of the stimulus to time the reflex reaches 10% and 90% of the maximum reflex amplitude. The time duration between 10% and 90% On Latencies is defined as the rise time. 90% and 10% Off Latencies refer to the time duration between the stimulus offset and the point where the reflex amplitude decreased to 90% and 10% of its maximum amplitude. Fall time is the duration from 90% to 10% Offset Latencies.

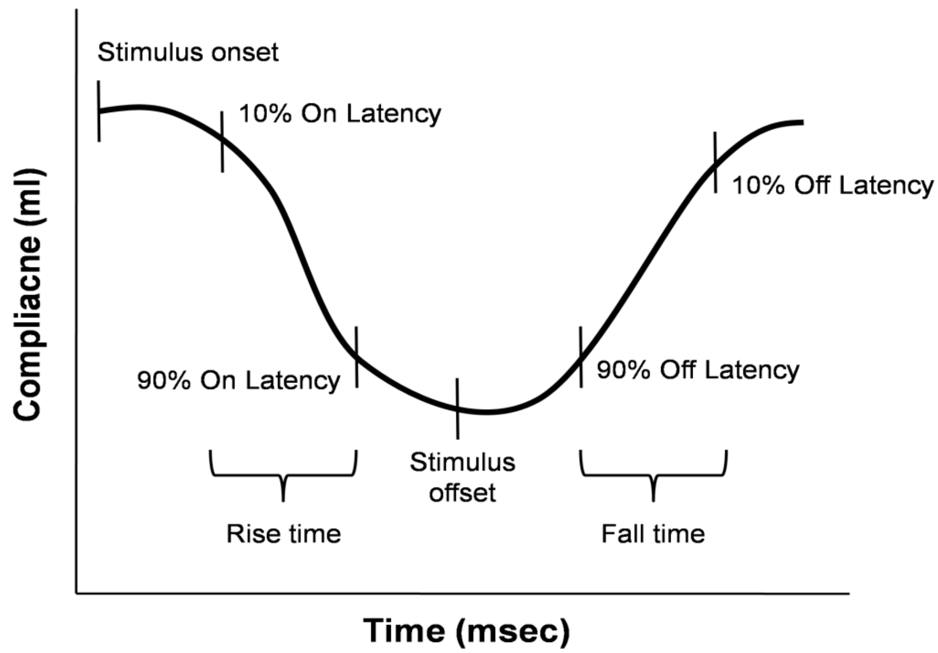

Figure 4.1: Parameters of reflex latencies measured in this study

4.2.2.2 Reflex decay

The Titan (Interacoustics, 2013) middle ear analyzer was used for measuring reflex decay. It was calibrated for intensity levels, compliance, volume and pressure according to the American National Standard Institute [ANSI] S3.39 (1987) standard. Crossed and uncrossed reflex decay was measured as the percentage change (decay value) that occurred in reflex amplitude between the initial steady amplitude and the amplitude following 15 seconds of a continuous stimulus presentation. Reflex decay measurements were conducted using a 226 Hz probe tone and a broadband activator stimulus presented at a level of 10 dB SL (ref acoustic reflex threshold). Acoustic reflex thresholds were established following the same methodology used in reflex latency measurements.

4.3 Results

4.3.1 Acoustic reflex latencies

Repeated measures ANOVA (RM-ANOVA) were used for data analysis. Significance values for ear, group, condition and frequency are summarized in Table 4.1. There was no ear difference for any reflex latency parameter. Further analyses were therefore conducted with values averaged across ears.

4.3.1.1 10% On Latency, 90% On Latency, 90% Off Latency and 10% Off Latency

Figure 4.2 shows mean and standard errors of acoustic reflex latencies (10% On Latency, 90% On Latency, 90% Off Latency and 10% Off Latency) averaged across ears. For all the figures mentioned in this section normal hearing adults, typically developing children, APD and clinical non-APD are shown in squares, circles, diamonds and triangles, respectively. Acoustic reflex latencies for crossed and uncrossed reflexes are represented by open and filled symbols, respectively.

Reflex latency parameter	F values (RM-ANOVA)			
	Ear	Group	Condition	Frequency
10% On Latency	0.799 (p=0.375)	1.937 (p=0.134)	29.247** (p=0.001)	61.934** (p<0.001)
90% On Latency	0.134 (p=0.715)	2.091 (p=0.112)	63.355** (<0.001)	101.393** (p<0.001)
90% Off Latency	0.536 (p=0.467)	0.106 (p=0.956)	4.476* (p=0.039)	23.457** (p<0.001)
10% Off Latency	0.021 (p=0.887)	0.622 (p=0.604)	12.563** (p=0.001)	1.048 (p=0.354)
Rise time	0.006 (p=0.936)	0.764 (p=0.519)	25.861** (p<0.001)	69.824 (p<0.001)
Fall time	0.273 (p=0.617)	0.729 (p=0.539)	9.122** (p=0.004)	4.759** (p=0.010)

*Significant at 5% level.
**Significant at 1% level.

Table 4.1: F and p values for ear, group, condition and frequency effect on 10% On Latency, 90% On Latency, 90% Off Latency, 10% Off Latency, rise time and fall time obtained using RM-ANOVA.

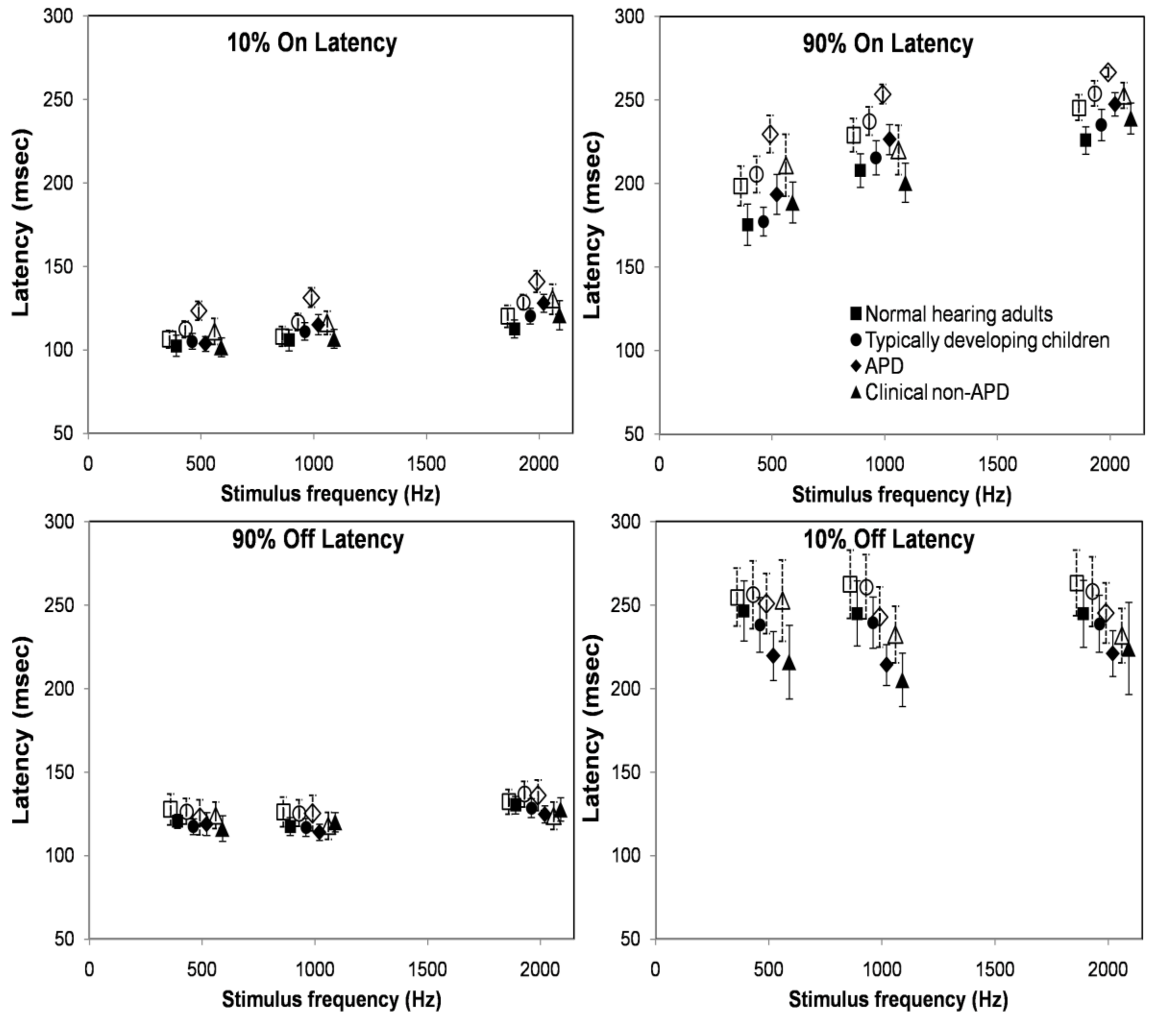

Figure 4.2: Mean of 10% On Latency, 90% On Latency, 90% Off Latency and 10% Off Latency averaged across right and left ear. Normal hearing adults, typically developing children, APD and clinical non-APD are shown in squares, circles, diamonds and triangles respectively. Acoustic reflex latencies for crossed and uncrossed reflexes are represented by open and filled symbols respectively. Error bars show $\underline{+}$1 standard error.

Although there was a tendency for mean onset latencies to be numerically slightly longer and mean offset latencies to be slightly shorter in children from the clinical groups in comparison to typically developing children and normal hearing adults there was no group effect for any reflex latency parameter including 10%

On Latency, 90% On Latency, 90% Off Latency and 10% Off Latency. This suggested no difference in the temporal aspects of the reflex in children with clinical listening complaints.

There was a significant effect of condition in all four latencies measures. For each parameter, reflex latencies were greater in the crossed condition when compared to the uncrossed condition, potentially reflecting the longer, more complex crossed pathways.

As can be seen in Figure 4.2 and Table 4.1 there was a trend for longer onset latencies with increase in frequency. The effect of frequency on offset latencies was inconsistent (Table 4.1). There was no significant frequency effect for 10% Off Latency. However, 90% Off Latency showed a significant frequency effect, but pairwise comparisons showed significantly greater 90% Off Latency only at 2000 Hz when compared to 500 ($p < 0.001$) and 1000 ($p < 0.001$) Hz. There was no significant difference between 90% Off Latency at 500 and 1000 Hz ($p = 0.308$).

4.3.1.2 Rise time and fall time

Figure 4.3 shows mean and standard error of rise time and fall time for acoustic reflexes averaged across right and left ears.

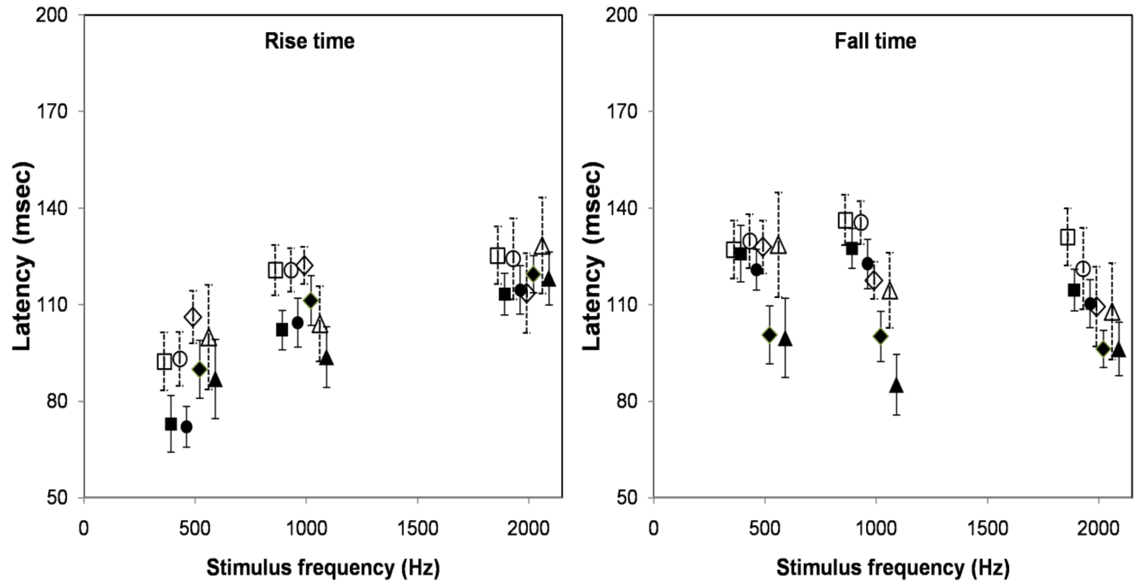

Figure 4.3: Mean and standard error of rise time and fall time for acoustic reflexes averaged across right and left ear. Normal hearing adults, typically developing children, APD and clinical non-APD are shown in squares, circles, diamonds and triangles respectively. Acoustic reflex latencies for crossed and uncrossed reflexes are represented by open and filled symbols respectively. Error bars show $\pm$1 standard error.

There was a tendency for mean fall time to be shorter in clinical children in comparison to typically developing children and normal hearing adults but there was no statistical difference between rise or fall time in children with suspected APD, typically developing children and normal hearing adults. Reflexes in the crossed condition had significantly longer rise time and fall time in comparison to the uncrossed condition.

Frequency effect was significant for both rise time and fall time but as with the measure of absolute latency the effect showed no clear pattern. Rise time tends to increase with the increase in stimulus frequency as can been seen in Figure 5.3. Fall time, in contrast, was shorter at 2000 Hz in comparison to 500 and 1000 Hz. Pairwise comparison in fall time showed significant difference only between at 500 and 2000 Hz ($p = 0.009$). Overall, the greatest interest of this study was to estimate the effect of group and condition on reflex latencies. Results suggested a significant effect of condition on latencies but there were no significant differences in latencies between groups.

4.3.2 Acoustic reflex decay

Figures 4.4 (right ear) and 4.5 (left ear) shows mean and standard error for crossed and uncrossed acoustic reflex decay in all 4 groups. RM-ANOVA showed no significant difference between right and left ear on reflex decay [$F(1, 34) = 0.068$, $p = 0.795$]. Decay in the crossed and uncrossed condition was statistically similar [$F(1, 34) = 0.307$, $p = 0.583$]. There was no statistically significant difference in reflex decay between groups [$F(3, 34) = 0.303$, $p = 0.823$].

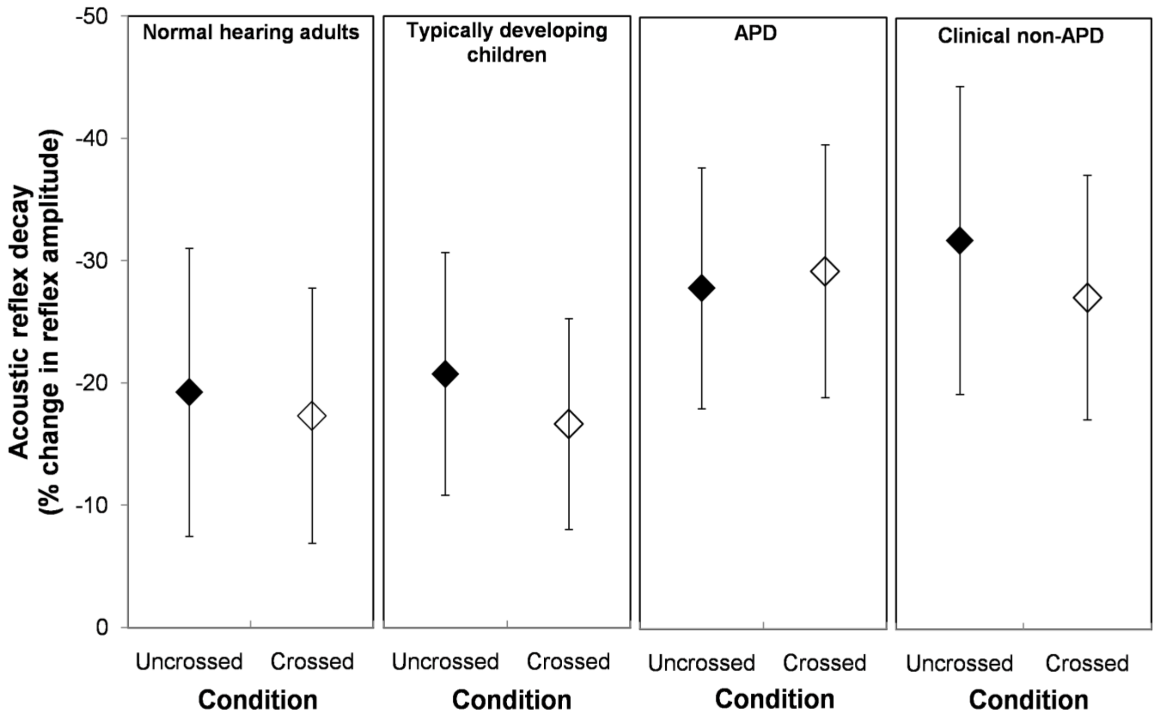

Figure 4.4: Mean of crossed and uncrossed acoustic reflex decay for right ear in normal hearing adults, typically developing children, APD and clinical non-APD. Error bars show +1 standard error.

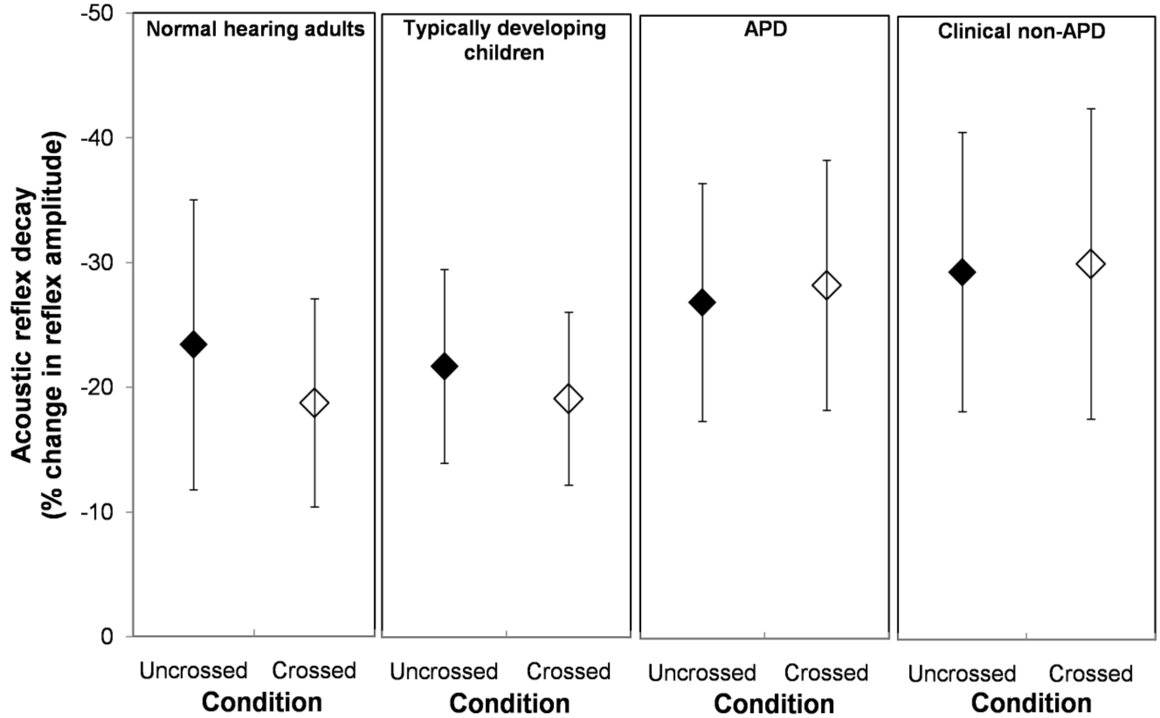

Figure 4.5: Mean and standard error of crossed and uncrossed acoustic reflex decay for left ear in normal hearing adults, typically developing children, APD and clinical non-APD Error bars show ±1 standard error.

4.4 Discussion

4.4.1 Acoustic reflex latencies

Acoustic reflex latencies were measured in normal hearing adults, typically developing children, APD and clinically referred children who did not receive APD diagnosis based on behavioral testing. Reflex latencies were similar in all groups. Crossed latencies were found to be longer in comparison to uncrossed latencies. There was no ear effect on reflex latencies. Reflex latencies showed a significant effect of stimulus frequency.

Clemis and Sarno (1980) and Qiu and Stucker (1998) reported no significant differences between crossed and uncrossed reflex latencies. The present study showed that the crossed condition resulted in slightly prolonged onset and offset latencies in comparison to the uncrossed condition, suggesting that crossed stimulation requires longer conduction times to activate the acoustic reflex. The anatomy of the crossed and uncrossed reflex pathways has been described and longer latencies in the crossed condition may be due to the greater number of neural synapses in the crossed pathway.

There is no previous report of ear effects on reflex latencies, but these findings are consistent with the results of other reflex measures including thresholds (Osterhammel & Osterhammel, 1979; Wilson et al., 1981) and growth functions (Sprague et al., 1981; Wilson et al., 1981). Chapter 2 and 3 of this thesis also suggested no ear differences in thresholds and growth functions, respectively.

4.4.2 Acoustic reflex decay

Statistically similar reflex decay values were found in children with suspected APD, typically developing children and normal hearing adults. There has been no previous study that investigated reflex decay in children with suspected APD. This study also showed no difference between crossed and uncrossed reflex decay, similar to the findings of Borg (1980) in which similar decay was reported for crossed and uncrossed reflex. Oviatt and Kinely (1979) reported greater decay for uncrossed reflexes in comparison to the crossed reflex but the difference did not reach significance.

4.5 General conclusion

Studies conducted in patients with tumors and brainstem abnormalities have shown prolonged reflex latencies and greater reflex decay. In this study there were no significant differences in either latencies or decay between children with clinical issues when compared to the adults and age matched controls.

Reflex latencies represent the neural conduction time across reflex pathway (Clemis & Sarno, 1980; Jerger & Haynes, 1983; Mangham et al., 1980;) and no difference in reflex latencies for children with suspected APD, typically developing children and normal hearing adult suggests no abnormality in neural conduction time for the reflex pathway in children with suspected APD.

Reflex decay was measured as the decrease in reflex amplitude over time. As reflex was measured with respect to the initial amplitude of acoustic reflex, small or larger amplitude at the onset of the acoustic reflex should have no effect on the measurement of reflex decay. Therefore, over the sustained duration of stimulus the amount of decrease in reflex amplitude in children with suspected APD is within the range of values seen in typically developing children and normal hearing adults. But previous studies in which we estimated reflex thresholds and growth functions in children with suspected APD showed abnormality in this clinical population which might indicate a deficit in the neural strength of the reflex pathway in children with suspected APD.

4.6 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. & Allan, C. (2014). Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

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

American National Standards Institue [ANSI] (1987) Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance). ANSI S3.39-1987. New York: American National Standards Institute.

Anderson, H., Barr, B., & Wedenberg, E. (1969). Intra-aural reflexes in retrocochlear lesions. In *Nobel symposium* (Vol. 10, pp. 49-55). Stockholm: Almqvist & Wiksell.

Anderson, H., Barr, B. & Wedenberg, E. (1970). Early diagnosis of VIIIth-nerve tumours by acoustic reflex tests. *Acta Oto-Laryngologica Supplement, 263,* 232-237.

Banai, K., & Kraus, N. (2007). Neurobiology of (central) auditory processing disorder and language-based learning disability. In G. D. Chermak & F. E. Musiek (Eds.), Handbook of (central) auditory processing disorders (pp. 89{116). San Diego: Plural Publishing.

Borg, E. (1976). Dynamic characteristics of the intra-aural muscle reflex.In A. S. Felfman & L.A. Wilber (Eds.), *Acoustic Impedance and Admittance. The Measurement of Middle Ear Function* (pp.236-299). Baltimore (Maryland): Williams & Wilkins.

Borg, E. (1980). Recovery of the human intra-aural muscle reflex after “pauses” of various depth. *Acta oto-laryngologica*, *90*(1-6), 1-5.

Borg, E. (1982). Time Course of the Human Acoustic Stapedius Reflex: A Comparison of Eight Different Measures in Normal-hearing Subjects.*Scandinavian audiology*, *11*(4), 237-242.

Bosatra, A., Russolo, M., & Silverman, C.A. (1984). Acoustic-reflex latency: Sate of the art. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Clemis, J.D. & Sarno, C.N. (1980). The acoustic reflex latency test: Clinical application. *Laryngoscope*, 90, 601-611.

Colletti, V. (1974). Some stapedius reflex parameters in normal and pathological conditions. *The Journal of Laryngology & Otology*, *88*(02), 127-137.

Gelfand, S.A. (2005). The acoustic reflex. In J. Katz (Ed.), *Handbook of clinical audiology: Fifth Edition* (pp: 205-232). Baltimore, MD: Lippincott Williams & Wilkins.

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.

Gopal, K.V. & Pierel, K. (1999). Binaural interaction component in children at risk for central auditory processing disorders. *Scandinavian Audiology*, 28, 77-84.

Gorga, M. P. & Stelmachowicz, P. G. (1983). Temporal characteristics of the acoustic reflex. *Audiology*, *22,* 120-127.

Hess, K. (1979). Stapedius reflex in multiple sclerosis. *Journal of Neurology, Neurosurgery & Psychiatry*, *42*(4), 331-337.

Hung, I. J. & Dallos, P. (1972). Study of the acoustic reflex in human beings. I. Dynamic characteristics. *The Journal of the Acoustical Society of America, 52 (4), 1972-80.*

Interacoustics (2013). *TITAN-Instruction for use.*

Ivey, R. G. (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.

Jerger, J., Harford, E., Clemis, J., & Alford, B. (1974). The acoustic reflex in eighth nerve disorders. *Archives of Otolaryngology—Head & Neck Surgery*,*99*(6), 409.

Jerger, J., & Hayes, D. (1983). Latency of the acoustic reflex in eigth nerve tumor. *Archives of Otolaryngology, 109,* 1-5.

Jerger, J., Oliver, T. A., & Stach, B. (1986). Problems in the clinical measurement of acoustic reflex latency. *Scandinavian audiology*, *15*(1), 31-40.

Jirsa, R.E. & Clontz, K. B. (1990). Long latency auditory event related potentials from children with auditory processing disorders. *Ear and Hearing, 11,* 222-232.

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

Lidén, G., Nilsson, E., Laaskinen, O., Roos, B. E., & Miller, J. (1974). The stapedius reflex and motor reaction time: a parallel investigation of the effect of drugs. *Scandinavian Audiology*, *3*(2), 73-80.

Lilly, D. J. (1984). Evaluation of the response time of acoustic-immittance instruments. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Mangham, C., Lindeman, R. & Dawson, W. (1980). Stapedius reflex quantification in acoustic tumor patients. Olsen, W. O., Stach, B. A., & Kurdziel, S. A. (1981). Acoustic reflex decay in 10 seconds and in 5 seconds for Meniere's disease patients and for VIIIth nerve tumor patients. *Ear and hearing*, *2*(4), 180-181.*Laryngoscope, 90*, 242-250.

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian journal of otorhinolaryngology*, *67* (7), 830-835.

Muchnik, C., Roth, D.A., Othman-Jebara, R., Putter-Katz, H., Shabtai, E.L. & Hildesheimer, M. (2004). Reduced medial olivocochlear bundle system function in children with auditory processing disorders. *Audiology & Neuro-Otology, 9*, 107-114. doi: 10.1159/000076001

Norris, T. W., Stelmachowicz, P., Bowling, C., & Taylor, D. (1974). Latency measures of the acoustic reflex: Normal versus Sensorineural. *International Journal of Audiology*, *13*(6), 464-469.

Osterhammel, D., & Osterhammel, P. (1979). Age and sex variationsfor the normal stapedial reflex thresholds and tympanometric compliance values. *Scandinavian Audiology*, *8*, 153-158.

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

Qiu, W.W. & Stucker, F.J. (1998). Characterization of acoustic reflex latency in normal-hearing subjects. *Scandinavian Audiology, 27*, 43-49.

Sanders, J. W., Josey, A. F., Glasscock, M. E., & Jackson, C. G. (1981). The acoustic reflex test in cochlear and eighth nerve pathology ears. *The Laryngoscope*, *91*(5), 787-793.

Sanches, S.G.G. & Carvallo, R.M. (2006). Contralateral suppression of transient evoked otoacoustic emissions in children with auditory processing disorder. *Audiology & Neurotology, 11*, 366-372.

Sheehy, J. L., & Inzer, B. E. (1976). Acoustic reflex test in neuro-otologic diagnosis: A review of 24 cases of acoustic tumors. *Archives of Otolaryngology*,*102*(11), 647-653.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope*, *95*, 811-817.

Wilson, R.H., Shanks, J.E. & Velde, T.M. (1981). Aural acoustic immittance measurements: Inter-aural differences. *Journal of Speech and Hearing Disorders, 46*, 413-421.

Wilson, R. H., Shanks, J. E. & Lilly, D. J. (1984). Acoustic-reflex adaptation. In: S. Silman (Ed.), The *acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Chapter 5

5 Effect of the Activation of Acoustic Reflex on Middle Ear Functioning in Normal hearing adults, Typically Developing Children and Children with Suspected Auditory Processing Disorder

5.1 Introduction

It has been suggested that activation of the middle ear muscle reflex modifies transmission of sound to the cochlea in a frequency selective way. Wiggers (1937) measured the effect of middle ear reflex on the cochlear electrogram in guinea pigs and reported that reflex activation results in reduced transmission below 1000 Hz, an improvement in the transmission between 1300 and 1800 Hz and no effect above 2000 Hz. Galambos and Rupert (1959) found a reduction in the cochlear potential in cats between 500 and 3000 Hz following the activation of the reflex.

Moller (1965) estimated the effect of the stapedius muscle contraction on the cochlear potential in cats and calculated the change in middle ear transmission, in dB, by measuring the sound pressure required to compensate for the change in the cochlear potential caused by the reflex activation. An attenuation of 1 to 9 dB was suggested for between 200 and 1500 Hz with the maximum reduction of 9 dB occurring at 700 Hz. A small gain of 1-2 dB was found between 1500 and 3000 Hz. Simmons (1964) found that the reflex activation caused an attenuation of 20 to 25 dB for sounds below 1000 Hz in cats. Nuttal (1974) reported that contraction of the tensor tympanic and stapedius muscles resulted in a reduction of 20 to 25 dB and 15 to 20 dB respectively in the transmission of frequencies below 1000 Hz. He also found that a contraction of tensor tympanic and stapedius muscles provided a gain of 5 dB and 0.5 dB respectively for the frequencies between 1000 and 3000 Hz. In human cadavers, Neergard, Anderden, Hansen and Jepsen (1963) measured the effect of the contraction of the stapedius muscle on the transmission of 125 to 3500 Hz pure tones. An attenuation of 10 to 15 dB was reported in the low frequency region below 1000 Hz. Comparatively, there was less attenuation at higher frequencies. Variations in the magnitude of the reflex effect reported in the reviewed literature is primarily due to the different methods by which the middle ear muscles were contracted (for example, acoustically or electrically).

Direct estimation of the effect of the middle ear muscle reflex on middle ear transmission in living humans is difficult. It can only be investigated by acoustically activating the reflex, and in humans it is the stapedius muscle that contracts in response to sound. Moller (1958) measured the absorption of a 785 Hz pure-tone by the middle ear with and without reflex activation. When the reflex was activated there was a decrease in the absorption of the pure-tone which increased with an increase in the reflex activator stimulus level. Borg (1968) estimated the effect of crossed reflex activation on sound transmission (in dB) in patients with short term stapedius muscle paralysis based on impedance measurements obtained before and after recovery from paralysis. It was reported that the crossed reflex can cause an attenuation of 12 to 15 dB and 0 to 6 dB for 500 and 1450 Hz pure tones, respectively.

The decrease in transmission of low frequency sound energy due to the activation of the acoustic reflexes is thought to be helpful in the perception of speech, especially in presence of noise (Simmons, 1964). Liden, Nordlund and Hawkins (1964) describe the function of the stapedius muscle contraction as similar to a high pass filter that ultimately improves the signal to noise ratio for high frequency sound which is important for speech perception. The important role of the acoustic reflex in speech perception in the presence of noise has been reported in several studies. Aiken, Andrus, Bance and Phillips (2013) suggested a possible role of the acoustic reflex in improving speech perception in noise by preventing upward spread of masking at moderate levels of noise. De Andrade et al. (2011) and Colletti, Fiorino, Verlato and Carner (1992) found that the acoustic reflex helps in reaching better performance in speech discrimination and frequency selectivity tasks. Dorman, Cedar, Hannley and Leek (1986) reported vowel recognition in listeners with normal reflexes improved when their reflexes were activated. Borg and Zakrisson (1974) found that ears with acute stapedius muscle paralysis had greater masking effect in comparison to ears with normal acoustic reflexes.

Difficulty understanding speech in the presence of noise is a common complaint from children with suspected auditory processing disorders (APD). Previous investigations have suggested acoustic reflex abnormalities in children with suspected APD (Allen & Allan, 2007, 2014; Meneguello et al., 2001; Thomas, McMurry & Pillsbury, 1985). Chapter 2 and 3 also showed reflex abnormalities in this population in terms of elevated or absent reflexes and shallower reflex growth functions, respectively in comparison to age matched controls and normal hearing adults. Knowing the contribution of the acoustic reflex in perceiving speech in the presence of noise makes it critical to investigate the impact of abnormal acoustic reflexes on middle ear function in children with suspected APD.

Middle ear absorbance provides an estimate of sound energy being absorbed by the middle ear across frequency. Absorbance is the ratio of acoustic energy absorbed by the middle ear to the acoustic energy of the incident sound (Keefe, Sanford, Ellison, Fitzpatrick & Gorga, 2012). A change in the absorbance (sound absorbed by the middle ear) following activation of the reflex could be used to demonstrate the effect of the reflex on middle ear function.

Another middle ear measurement that could be used to estimate the effect of the acoustic reflex on middle ear function is the middle ear resonant frequency. The resonant frequency of the middle ear transmission system is the frequency at which mass susceptance and stiffness susceptance cancel each other and only conductance contributes to the compliance of the middle ear. Resonant frequency is reported to change when there is a change in the mass or stiffness of the middle ear system (Hanks & Mortensen, 1997). For example, resonant frequency lowers when there is an increase in the mass of the middle ear and resonant frequency rises to a higher frequency with an increase in the stiffness of the middle ear. Stiffness of the ossicular chain increases when the reflex activates which ultimately increases the stiffness of the middle ear as is evident with the decrease in compliance following the onset of the reflex. This increase in stiffness of the middle ear due to the reflex activation might also change the resonant frequency of the middle ear. The aim of this study was to investigate the effect of crossed reflex activation on absorbance and resonant frequency in children with suspected APD, typically developing children and normal hearing adults.

5.2 Method

5.2.1 Participants

Participants in this study included 12 normal hearing adults (18-30 years of age), 13 typically developing children (7 to 15 years of age) and 20 children (aged 7 to 15 years) suspected of having an auditory processing disorder. The children suspected of having an auditory processing disorder were referred to the Child Hearing Research Laboratory by caregivers, teachers, parents, and physicians for APD assessment. All the participants had normal otoscopic examination, normal hearing thresholds (American-Speech-Language-Hearing-Association [ASHA], 2005), normal middle function (ASHA, 1988) and no history of neurologic disorder.

5.2.2 Procedure

Absorbance and resonant frequency were measured in the resting state and then while activating the reflex at three reflex activator intensity levels (acoustic reflex threshold [ART], ART + 5 dB and ART + 10 dB) in the crossed condition. Crossed ARTs were elicited using a wide band noise (400-12000 Hz) presented in 5 dB steps using the TITAN middle ear analyzer (Interacoustic, 2013). Reflex amplitude of 0.02 ml or more was considered the criteria for establishing ART. Validation of acoustic reflex measures was done by repeating the measure two times at the same stimulus level. The TITAN was professionally calibrated for stimulus intensity level, volume and pressure measurements according to the American National Standard Institute [ANSI] S3.39 (1987) standard. The reflex thresholds were measured in dB HL and then converted to dB SPL using the Interacoustic standard reference equivalent threshold sound pressure level value for wide band noise (Interacoustic, 2013). Similar wide band noise (400 -12000 Hz) was generated using the FIR- Kaiser Window design in MATLAB. This wide band noise was produced by a Lenovo laptop in conjunction with the CAVRA device (Meng, 2009) which operates as a sound card and attenuator. The signal was presented through EAR 3A insert ear phones at the desired SPL levels in order to activate the crossed reflex while absorbance was estimated under the influence of the reflex. In all participants, absorbance and resonant frequency were measured in the right ear and the crossed reflex was activated by stimulating the left ear. For any measurement, the intensity level of the wide band noise was not increased above100 dB SPL. Therefore individuals who had reflexes above 100 dB SPL were not considered for absorbance and resonant frequency measurements. Also, testing was not completed if the sounds were uncomfortable for the participants.

5.2.3 Data analysis for absorbance

Absorbance measured without activating a reflex was considered the baseline absorbance. Absorbance was also measured in the presence of the activated reflex at ART, ART + 5 dB and ART + 10 dB. To estimate the effect of the acoustic reflex on absorbance, the baseline absorbance was subtracted from the absorbance measured during reflex activation. This calculation provided the change in absorbance when the acoustic reflex was activated at three different activator stimulus intensity levels. The Titan provides absorbance values across the frequency range of 226 to 8000 Hz. For the purposes of this study absorbance from 226 to 4000 Hz was included in the analysis. Figure 5.1 shows the baseline absorbance and absorbance measured by activating the reflex at threshold for an adult participant (A). It also shows the difference between both absorbance measures for the participant (B).

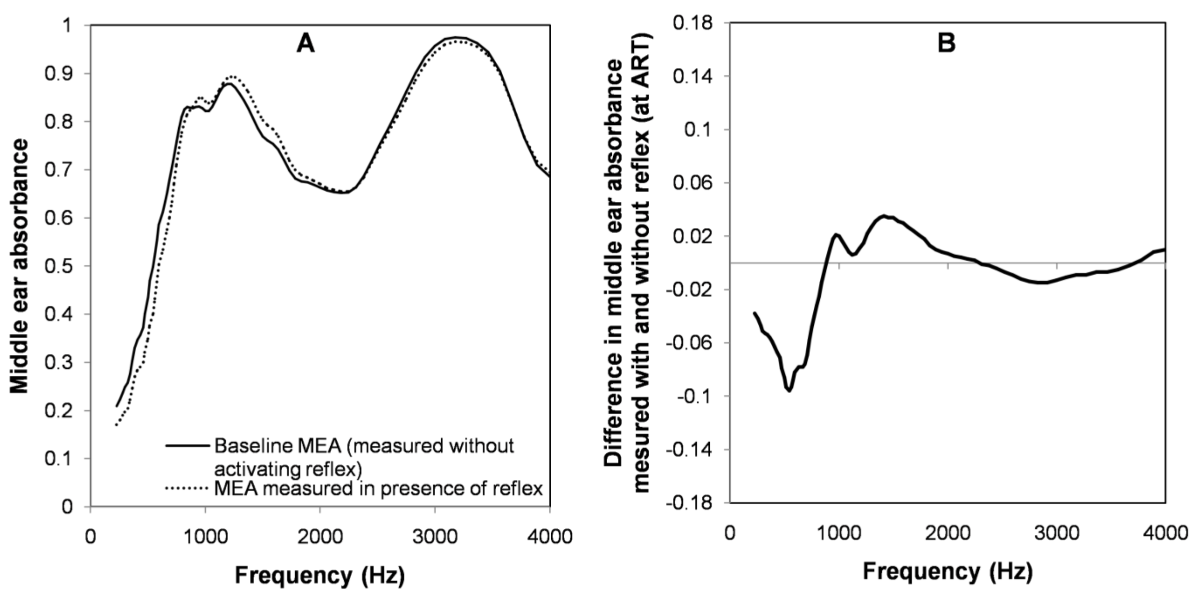

Figure 5.1: Example of baseline absorbance and absorbance measured with activation of the acoustic reflex at threshold (A). Also shown in the figure is the difference between the same absorbance measured with and without activating reflex (B)

5.3 Results

Three children with suspected APD had absent reflexes and therefore were excluded from the study. Additionally, one typically developing child and 4 children with suspected APD were not considered for the absorbance and resonant frequency measures because they had crossed ARTs above 100 dB SPL. Measurements of absorbance and resonant frequency were completed in the remaining 37 participants. Measurements in the presence of acoustic reflex activation in some participants with elevated crossed reflexes were limited because signals above 100 dB SPL were not employed. Measurements were obtained with all participants at the intensity level that first activated the reflex (ART). Measurements in the presence of a reflex activated at the intensity level of ART + 5 dB were obtained in all the participants except one child with suspected APD. Absorbance and resonant frequency measures in the presence of the crossed reflex activated at an intensity level of ART + 10 dB were not obtained in 4 normal hearing adults, 5 typically developing children and 10 children with suspected APD.

5.3.1 Effect of reflex activation on absorbance

Figure 5.2 shows the change in absorbance due to the activation of the crossed reflex in normal hearing adults, typically developing children and children with suspected APD. The change in absorbance is shown as the difference in absorbance measured with and without the activation of the crossed reflex between 226 and 4000 Hz. Mean change in absorbance is represented by a solid black line and individual data with grey lines. Absorbance change at different activator intensity levels i.e. ART, ART + 5dB and ART +10 dB are shown in the first, second and third row of plots, respectively. Mean data suggest that the effect of reflex on absorbance varied with frequency. There was a decrease in absorbance between 226 and 1000 Hz in all the groups. A small increase in absorbance was seen at approximately 1000 to 2000 Hz. Little or no change in absorbance was observed above 2000 Hz.

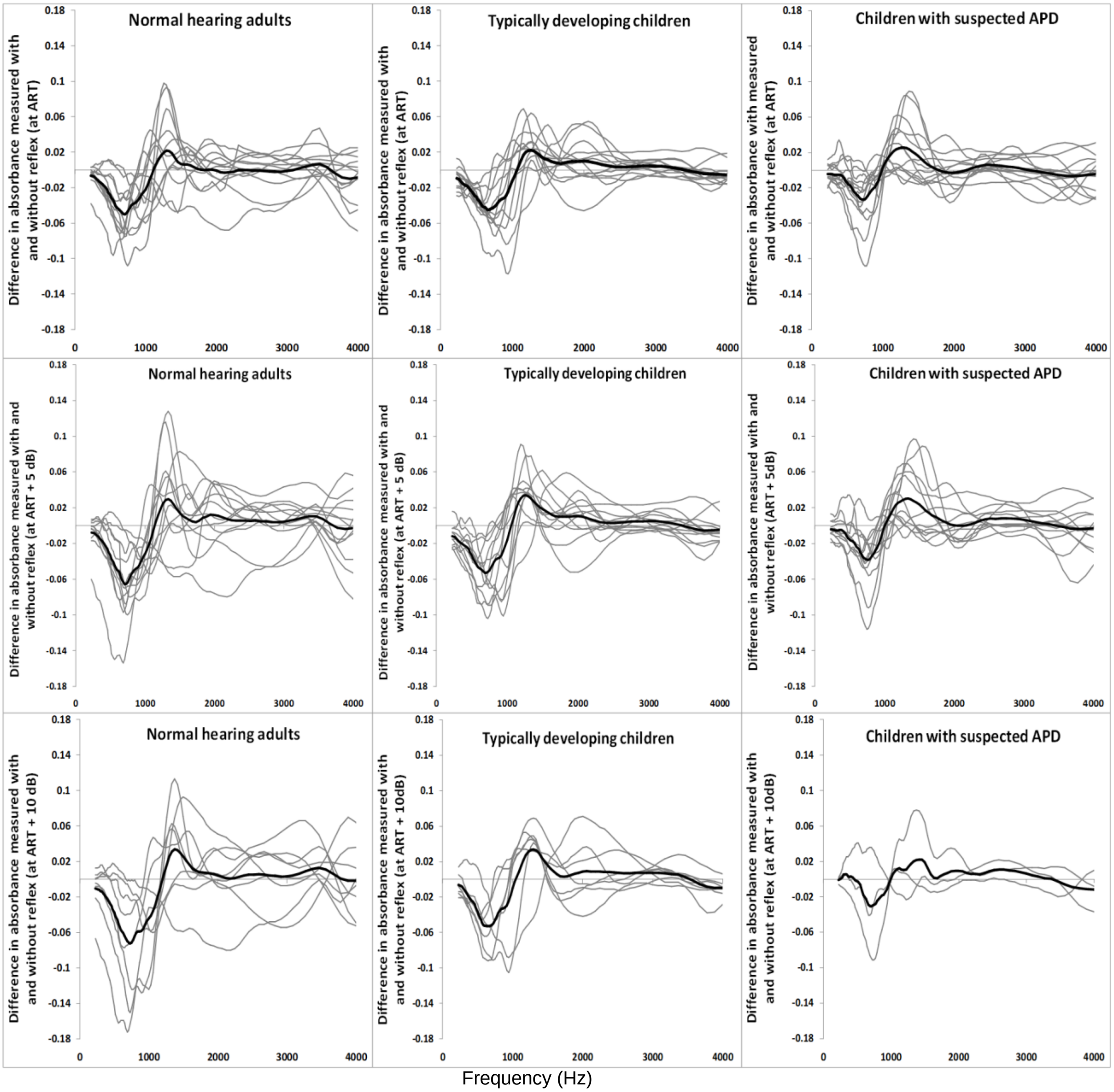

Figure 5.2: Mean difference in absorbance measured with and without the activation of crossed reflex between 226 and 4000 Hz. Results from normal hearing adults, typically developing children and children with suspected APD are shown in the first, second and third columns respectively. Absorbance change at different activator intensity levels i.e. ART, ART + 5dB and ART +10 dB are shown in first, second, and third rows respectively. Mean change in absorbance is represented by the solid black line and individual data with grey lines.

Statistical analysis was not done on the absorbance change measured by activating the reflex at ART +10 dB as there was a lack of data at this stimulus level. One child with suspected APD was also excluded from the statistical analysis as measurement was not done for all the conditions of reflex activator.

5.3.1.1 Effect of reflex activation on absorbance between 226 and 1000 Hz

Mean data suggested that reflex activation causes a decrease in the absorbance between 226 and 1000 Hz. For the purpose of statistical analysis the magnitude and frequency at the point of maximum absorbance decrease was derived for all participants. One child with suspected APD who did not demonstrate any decrease in absorbance at the ART + 5 dB reflex activator condition in this frequency range was not included in the analysis.

Repeated measures ANOVA (RM-ANOVA) showed that the magnitude of the maximum decrease in absorbance was significantly different [F (1, 32) = 9.565, p = 0.004] for the two reflex activator conditions (ART and ART + 5 dB) but there was no group effect [F (2, 32) = 1.595, p = 0.219]. There was no interaction between groups and conditions which suggests that all groups had a similar decrease in maximum absorbance for both activator conditions [F (2, 32) = 0.641, p = 0.533].

The frequency at which the maximum change in absorbance occurred did not change for the two conditions of reflex activator [F (1, 32) = 0.835, p =

0.368].There was no group effect [F (2, 32) = 2.054, p = 0.145]. Similar to the magnitude of the maximum decrease in absorbance, the frequency did not show any group-condition interaction [F (2, 32) = 0.296, p = 0.746] which points toward similar frequencies at which the maximum decrease occurred in all groups.

5.3.1.2 Effect of reflex activation on absorbance between 1000 and 2000 Hz

Between 1000 and 2000 Hz the magnitude and frequency of the maximum absorbance increase was derived for each participant for the purpose of statistical analysis. Two adults were not included in the analysis as they did not show increased absorbance in this frequency range at one or more reflex activator levels.

The effect of increasing reflex activator level was significant for the magnitude [F (1, 31) = 11.542, p = 0.002] of the maximum absorbance increase but there was no change in frequency [F (1, 31) = 0.216, p = 0.645] when the reflex was activated at a higher level. The effect of condition on the magnitude [F (2, 31) = 0.661, p = 0.524] and frequency [F (2, 31) = 1.066, p = 0.357] of maximum absorbance increase was statistically similar in all groups. As there was no group-condition interaction for magnitude [F (2, 31) = 1.086, p = 0.350] or frequency [F (2, 31) = 1.877, p = 0.170] of maximum absorbance increase, it can be suggested that all groups had similar magnitude and frequency at the point of maximum absorbance increase.

Figure 5.3 shows maximum decrease between 226 and 1000 Hz (top panel) and maximum increase between 1000 and 2000 Hz (bottom panel) in absorbance for all the participants at different activator intensity levels i.e. ART, ART + 5dB and ART +10 dB. Negative values in the top panel indicate decrease in absorbance. Children with suspected APD, typically developing children and normal hearing adults are shown by unfilled black diamonds, filled black circles and filled black squares, respectively. The figure includes all participants who showed decrease in absorbance between 226 and 1000 Hz and increase in absorbance between 1000 and 2000 Hz. Means of maximum decrease or increase in absorbance in children with suspected APD, typically developing children and normal hearing adults are shown by red diamonds, red circles and red squares (unfilled symbols) respectively.

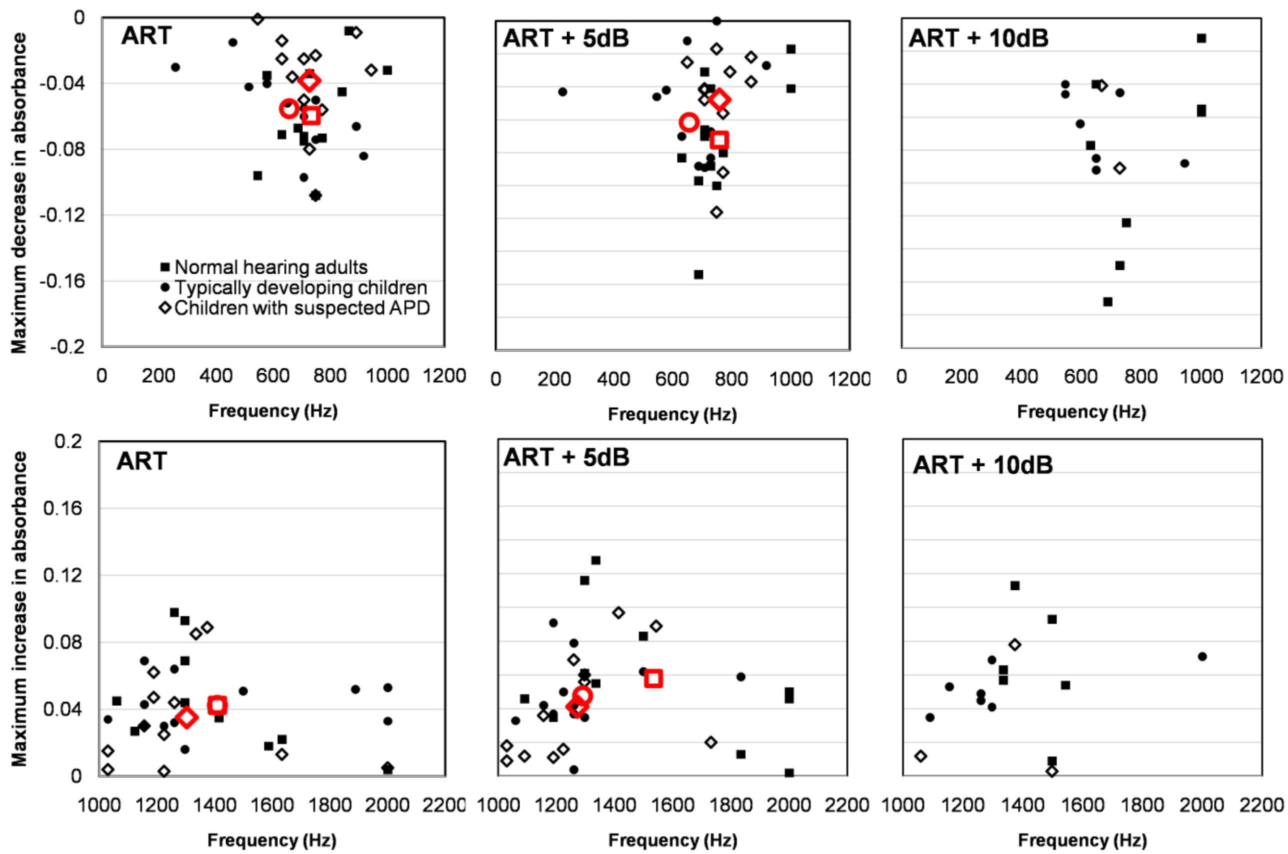

Figure 5.3: Maximum decrease between 226 and 1000 Hz (top panel) and increase between 1000 and 2000 Hz (bottom panel) in absorbance for different activator intensity levels i.e. ART, ART + 5dB and ART +10 dB. Children with suspected APD, typically developing children and normal hearing adults are shown by unfilled black diamonds, filled black circles and filled black squares respectively. Means of maximum decrease or increase in absorbance in children with suspected APD, typically developing children and normal hearing adults are shown by red diamonds, red circles and red squares (unfilled symbols) respectively.

Although all groups showed statistically similar magnitude of maximum decrease and increase in absorbance following reflex activation, abnormalities in children with suspected APD can be clearly seen in Figures 5.2 and 5.3. Only some children with suspected APD had maximum decrease or increase of the order of typically developing children and normal hearing adults. This is also true for the effect of increasing activator level, from ART to ART + 5 dB, on the magnitude of maximum absorbance change. The effect was limited to the children with suspected APD who had absorbance changes similar to that of control groups. Absorbance change could not be obtained at ART + 10 dB reflex activator condition from many participants, especially in the groups of clinical children. Interpretation of the results based on the data at this reflex activator condition, could be misleading.

5.3.2 Effect of reflex activation on resonant frequency

Statistical analysis was conducted to investigate the effect of reflex activation on resonant frequency. Resonant frequency measured by activating the reflex at ART +10 dB was not part of the statistical analysis because of a lack of data at this presentation level. Additionally 1 child with suspected APD in whom resonant frequency was measured only at the ART activator level was excluded from the statistical analysis. Figure 5.4 shows the mean and standard error of the resonant frequency measured without activating the reflex and measured at two reflex activator levels (ART and ART + 5 dB) in normal hearing adults, typically developing children and children with suspected APD.

RM-ANOVA revealed a significant effect of reflex activation on resonant frequency [$F(2, 32) = 23.241$, $p < 0.001$]. Pairwise comparisons showed that resonant frequency measured without activating the reflex was significantly different from the resonant frequency measured in presence of a reflex activated at ART ($p < 0.001$) and ART + 5 dB ($p < 0.001$). There was no significant difference between resonant frequency measured under reflex activator at ART and ART + 5 dB ($p < 1.000$). No group effect was evident for the resonant frequency measured with and without activating the acoustic reflex [F (2, 33) = 0.295, $p = 0.746$].

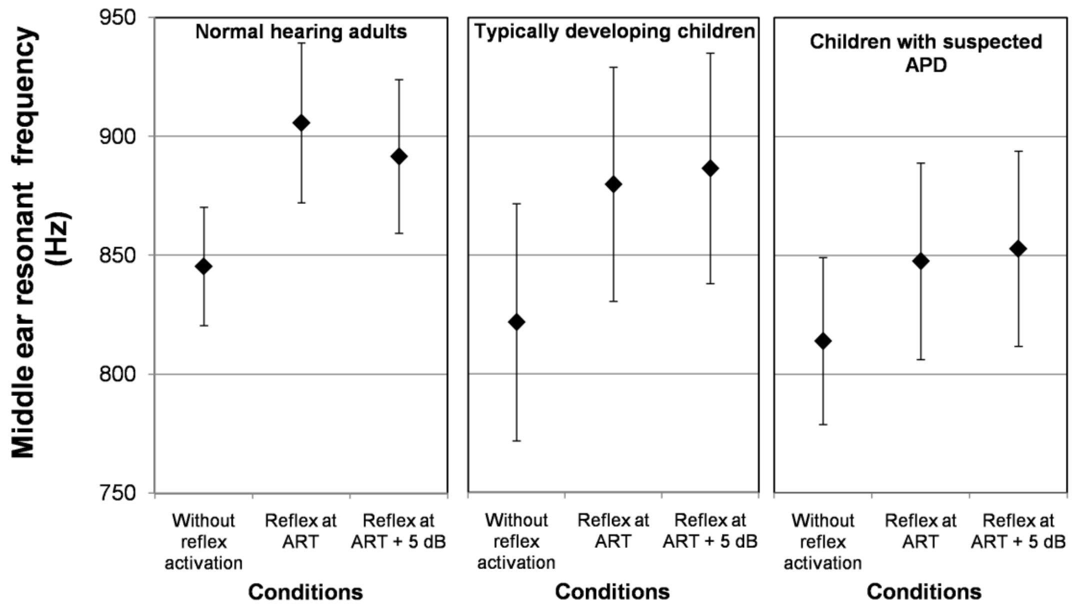

Figure 5.4: Mean and standard error of resonant frequency measured without activating the reflex and under the influence of reflex activation at two reflex activator levels: ART and ART + 5 dB. Error bars show $\pm$1 standard error.

5.4 Discussion

5.4.1 Effect of reflex activation on absorbance

The effect of acoustic reflex activation on middle ear function was measured in terms of change in absorbance. The activation of the acoustic reflex resulted in a frequency specific effect on absorbance. Between 226 and 1000 Hz, reflex activation caused a decrease in absorbance but between 1000 and 2000 Hz absorbance increased following reflex activation. No effect on absorbance was observed above 2000 Hz upon reflex activation. Studies completed to estimate the effect of reflex activation on middle ear transmission have suggested similar frequency specific effects following activation of the acoustic reflex (Borg, 1966; Moller, 1957; Neergard, Anderden, Hansen & Jepsen, 1956; Nuttal, 1974; Simmons, 1964; Wiggers, 1937).

Feeney and Keefe (1999, 2001) estimated crossed acoustic reflex thresholds by measuring the change in middle ear reflectance by stimulating the contralateral ear in normal hearing adults. Data from that study showed changes in the reflectance of the probe ear when the stimulus level in the contralateral ear was at or above reflex threshold. Following reflex activation there was an increase in the reflectance between 226 and 1000 Hz and a decrease in reflectance between 1000 and 2000 Hz. There was little or no change in reflectance measured between 2000 to 4000Hz.

Middle ear reflectance and absorbance are related measures such that absorbance is equal to 1 minus middle ear reflectance (Liu et al. 2008). Any change in reflectance should be approximately equal to the change in absorbance but the direction of change will be in the opposite direction such that an increase in reflectance will correspond to a decrease in absorbance. In the present study, the magnitude of absorbance change and the frequency range at which the change occurred for normal hearing adults were similar to the changes in reflectance caused by the reflex activation reported by Feeney and Keefe (1999, 2001).The effect of increasing the reflex activator level was also similar in the two studies.

In the present study the absorbance change was not calculated in dB because it was not possible to estimate the actual power of the sound energy as absorbance is an estimate of the ratio of the sound energy incident into the ear and the sound energy absorbed by the middle ear. Feeney and Keefe (1999, 2001) gave an estimate of reflectance change in dB. It varied from1 to 2.5 dB at reflex threshold and from 2.5 to 7.5 at 16 dB above ART in the low frequency region (below 1000 Hz). The maximum increase between 1000 and 2000 Hz at the highest reflex activator was 0.75 dB. Since the reflex effect on absorbance measured in this study was similar to that of reflectance measured by Feeney and Keefe (1999, 2001), similar changes in absorbance in dB due to the reflex activation may be suggested.

One can argue over the difference in the amount of dB change caused by the activation of reflex in absorbance/reflectance and in middle ear transmission. Change in absorbance/reflectance gives an estimate of the increase or decrease in sound energy going into the middle ear. Cochlear potential are measured at the oval window to estimate the change in middle ear transmission (in non-human animals). These two measures will obviously be different as the middle ear itself provides a gain up to 30 dB (Kurokawa & Goode, 1995). But they are related in a way because transmission of sound through the middle ear in dependent upon the sound absorbed by the middle ear. So if at a certain frequency less sound energy is absorbed then at that frequency, transmission will also be reduced. Thus the effect of reflex on either absorbance or transmission will show similar changes in terms of increase or decrease across frequency. An explanation about the relationship between absorbance and transmission change comes from the measurement of absorbance in individuals with conductive hearing loss (Keefe et al., 2012). Even smaller changes in absorbance (less than 0.1) were associated with in an air bone gap of 30 dB. Similar changes in absorbance due to reflex activation found in this study and by Feeney and Keefe (1999, 2001) could therefore possibly cause a decrease in transmission similar to what has been shown in animal studies (Borg, 1966; Moller, 1957; Neergard, Anderden, Hansen & Jepsen, 1956; Nuttal, 1974; Simmons, 1964; Wiggers, 1937).

The change in absorbance resulting from acoustic reflex activation further strengthens the theory of the role of the acoustic reflex in speech perception, especially in the presence of noise. Reflex activation not only causes a reduction in the absorbance of low frequency sound where noise is predominant, but also an increase in the absorbance of higher frequencies important in speech perception, thereby improving the overall signal to noise ratio.

There is some debate in the literature about the intensity levels at which the reflex activates and whether, at those levels, reflex activation will help in speech perception. Often it is suggested that reflexes activate at very high stimulus levels. But activation of the reflex depends on bandwidth of the signal (Gelfand, 1984). Studies have reported activation of crossed reflexes occurring at moderate levels for broadband sounds (Gelfand, 1984; Feeney & Keefe, 1999, 2001; Wilson, 1981). Reflex thresholds are also reliant on the measurement systems (Feeney & Keefe, 1999, 2001). Crossed reflex thresholds measured using a reflectance system were reported to be 8 to 24 dB lower than reflex thresholds measured with a clinical system (Feeney & Keefe, 1999, 2001). In addition, reflex thresholds estimated using invasive techniques in animals are suggested to be as low as 40 dB (Simmons, 1959). It is possible that activation of the reflex may provide help in speech perception when the noise is presented at even moderate levels. Previously, Aiken et al. (2013) and Simmons and Beatty (1962) suggested that the acoustic reflex has a role in speech perception in noise at moderate levels.

Only a few children with suspected APD showed the reflex effect comparable to normal hearing adults and typically developing children. Most children with suspected APD showed much diminished reflex effects especially for the frequencies between 226 and 1000 Hz even when their thresholds were within normal limit. Noise is predominant in the low frequency region and reflex causes reduction in the transmission of sound in this frequency region that can be important for speech perception in the presence of noise. Considering the effect of reflex on absorbance in this study, a limited benefit in speech perception in noise can be suggested in children with suspected APD.

The effect of increasing reflex activator level was found to be statistically similar in all groups when only measured at 2 points although the broader frequency effect were suggestive of groups trends towards less increase in the clinical group. Children with suspected APD were included in the study irrespective of the presence or absence of abnormality in thresholds or reflex growth functions. This may have limited the ability to see group trends.

5.4.2 Effect of reflex activation on resonant frequency

Activation of the acoustic reflex caused a significant increase in resonant frequency in all groups. An increase in resonant frequency under the influence of acoustic reflex activation was also reported by Moller (1960) and Simmons (1959). The middle ear plays a crucial role in the transmission of sound as it acts as a transformer between the air in the external ear canal and the cochlear fluid, providing a gain of up to 22 times the signal sound pressure level. Gain is optimum at the resonant frequency (Boillat, 1989). Puria (2003) found that the maximum forward gain provided by the middle ear system was 18 dB at 900 Hz which is approximately equivalent to the resonant frequency. A small change in the resonant frequency may therefore have an important impact on the transmission of sound to the cochlea. Reflex activation did not cause a large change in resonant frequency, but for speech perception in the presence of noise even a small shift towards a higher frequency would enable better transmission (more gain) of those frequencies that are important for speech perception. Because noise is predominant in lower frequencies, an improvement in the signal to noise ratio caused by the small shift in resonant frequency may help with speech recognition in the presence of noise.

The magnitude of the effect of the acoustic reflex activation on resonant frequency was statistically similar in children with suspected APD, typically developing children and normal hearing adults. However mean values indicated a numerically smaller shift in resonant frequency in children with suspected APD in comparison to typically developing children and normal hearing adults. Considering the possible role of an increase in resonant frequency in improving the signal to noise ratio and potential benefit to speech in noise perception, an insufficient increase in resonant frequency upon reflex activation might have little value for children with suspected APD.

Due to some technical limitations of the TITAN, only the effect of the crossed reflex could be investigated. The magnitude of the reflex is reported to be larger when the reflex is activated in the uncrossed condition as compared to the crossed condition (Hall, 1982). Uncrossed acoustic reflex thresholds are also reported to be lower than the crossed reflex thresholds (Fria, LeBlanc, Kristensen & Alberti, 1975; Gelfand, 2005; Jerger, Hayes, Anthony & Mauldin, 1978; Moller, 1961, 1962). The results of this study suggested that higher activation resulted in greater effects. Therefore the benefits from the activation of the uncrossed reflex are expected to be larger and to occur at lower noise levels than that of the crossed reflex.

5.5 Conclusion

This study revealed that activation of the acoustic reflex results in an overall decrease of sensitivity at low frequencies. It was evident that an attenuation of low frequencies and a shift of resonant frequency towards higher frequencies occurred under the influence of the acoustic reflex. In addition, an increased absorbance of frequencies between 1000 and 2000 was also found to occur upon acoustic reflex activation. These combined actions might aid in reducing the negative impact of noise on speech perception by improving signal to noise ratio.

Previous studies have suggested abnormal reflexes in children with suspected APD. The results of the present study also suggested that even when reflexes were present, the effects of the acoustic reflex activation may have been reduced in some children with suspected APD. These findings can be related to the most commonly reported problem of difficulty understanding speech in presence of noise in children with suspected APD.

5.6 Reference

Aiken, S. J., Andrus, J. N., Bance, M., & Phillips, D. P. (2013). Acoustic Stapedius Reflex Function in Man Revisited. *Ear and hearing*, *34*(4), e38-e51.

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., Allan, C. 2014. Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

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

American National Standards Institue [ANSI] (1987) Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance). ANSI S3.39-1987. New York: American National Standards Institute.

Boillat, M. A. Sensory systems: The Ear. (1998). In: J. M. Stellman (Ed.), *Encyclopaedia of occupational health and safety*. Gevneva: International labor office.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *Acta Oto-laryngologica, 66*, 461-472.

Borg, E. Counter, S. A. & Rosler, G. (1984). Theories of middle ear muscle function. In: S. Silman (Ed.), *The acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Borg, E., & Zakrisson, J. E. (1974). Stapedius reflex and monaural masking. *Acta oto-laryngologica*, *78*(1-6), 155-161.

Colletti, V., Fiorino, F.G., Verlato, G. & Carner, M. (1992). Acoustic reflex in frequency selectivity: Brain stem auditory evoked response and speech discrimination. In J. Katz, N.A. Stecker & D. Henderson (Eds.). *Central Auditory Processing: A Transdisciplinary View* (pp. 39-46). St. Louis, MO: Mosby - Year Book, Incorporated.

De Andrade, K.C.L., Camboim, E.D., Soares, I.D.A., Peixoto, M.V.D.S., Neto, S.C., Menezes, P.D.L. (2011). The importance of acoustic reflex for communication. *American Journal of Otolaryngology – Head and Neck Medicine and Surgery, 32*, 221-227.

Dorman, F., Lindholm, J. M., Hannley, M. T., & Leek, M. R. (1987). Vowel intelligibility in the absence of the acoustic reflex : Performance-intensity characteristics. *The Journal of the Acoustical Society of America 81(2),* 562–564.

Feeney, M. P., & Keefe, D. H. (1999). Acoustic reflex detection using wide-band acoustic reflectance, admittance, and power measurements. *Journal of speech, language, and hearing research*, *42*(5), 1029-1041.

Feeney, M. P., & Keefe, D. H. (2001). Estimating the acoustic reflex threshold from wideband measures of reflectance, admittance, and power. *Ear and hearing*, *22*(4), 316-332.

Fria, T., LeBlanc, J., Kristensen, R., & Alberti, P. W. (1974). Ipsilateral acoustic reflex stimulation in normal and sensorineural impaired ears: a preliminary report. *Canadian journal of otolaryngology*, *4*(4), 695-703.

Galambos, R., & Rupert, A. (1959). Action of the middle ear muscles in normal cats. *The Journal of the Acoustical Society of America*, *31*(3), 349-355.

Gelfand, S. A. (1984). The contralateral acoustic reflex threshold. In: S. Silman (Ed.), *The acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Hall, J.W. (1982). Quantification of the relationship between crossed and uncrossed acoustic reflex amplitudes. *Ear and Hearing*, 3, 296-300.

Hanks, W. D., & Mortensen, B. A. (1997). Multifrequency tympanometry: effects of ear canal volume compensation on middle ear resonant. *Journal of the American Academy of Audiology*, *8*(1), 53-58.

Interacoustics (2013). *TITAN-Instruction for use.*

Jerger, J., Hayes, D., Anthony, L. & Mauldin, L. (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Monographs in Contemporary Audiology*, *1*, 1-20.

Keefe, D. H., Sanford, C. A., Ellison, J. C., Fitzpatrick, D. F., & Gorga, M. P. (2012). Wideband aural acoustic absorbance predicts conductive hearing loss in children. *International journal of audiology*, *51*(12), 880-891.

Kurokawa, H., & Goode, R. L. (1995). Sound pressure gain produced by the human middle ear. *Otolaryngology--Head and Neck Surgery*, *113*(4), 349-355.

Liden, G., Nordlund, B., & Hawkins, J. E. (1964). Significance of the stapedius reflex for the understanding of speech. *Acta Oto-Laryngologica*, *57*(S188), 275-279.

Liu, Y. W., Sanford, C. A., Ellison, J. C., Fitzpatrick, D. F., Gorga, M. P., & Keefe, D. H. (2008). Wideband absorbance tympanometry using pressure sweeps: System development and results on adults with normal hearing. *The Journal of the Acoustical Society of America*, *124*(6), 3708-3719.

Meng, Q. (2009). *Design and evaluation of portable psychoacoustic testing systems* (Unpublished masters' dissertation). The University of Western Ontario, London, Ontario, Canada.

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian journal of otorhinolaryngology*, *67* (7), 830-835.

Møller, A. R. (1958). Intra-Aural muscle contraction in man, examined by measuring acoustic impedance of the ear. *The Laryngoscope*, *68*(1), 48-62.

Moller, A. R. (1961). Bilateral contraction of the tympanic muscles in man examined by measuring acoustic impedance-change. *The Annals of otology, rhinology, and laryngology*, *70*, 735.

Moller, A.R. (1962). Acoustic reflex in man. *The Journal of the Acoustical Society of America*, *34*, 1524-1534.

Møller, A. R. (1965). An experimental study of the acoustic impedance of the middle ear and its transmission properties. *Acta oto-laryngologica*, *60*(1-6), 129-149.

Moller, A. R. (1984). Neurophysiological basis of the acoustic middle ear reflex. In: S. Silman (Ed.), *The acoustic reflex: Basic principle and clinical applications*. Orlando: Academic press.

Mukerji, S., Windsor, A. M., & Lee, D. J. (2010). Auditory brainstem circuits that mediate the middle ear muscle reflex. *Trends in Amplification*, *14*(3), 170-191.

Neergaard, E. B., Andersen, H. C., Hansen, C. C., & Jepsen, O. (1963). Experimental studies on sound transmission in the human ear. III. Influence of the stapedius and tensor sympani muscles. *Acta oto-laryngologica. Supplementum*, *188*, 280-286.

Nuttall, A. L. (1974). Tympanic muscle effects on middle-ear transfer characteristic. *The Journal of the Acoustical Society of America*, *56*(4), 1239-1247.

Puria, S. (2003). Measurements of human middle ear forward and reverse acoustics: implications for otoacoustic emissions. *The Journal of the Acoustical Society of America*, *113*(5), 2773-2789.

Simmons, F. B. (1959). Middle ear muscle activity at moderate sound levels.*The Annals of otology, rhinology, and laryngology*, *68*, 1126.

Simmons, F. B. (1964). Perceptual theories of middle ear muscle function. *The Annals of otology, rhinology, and laryngology*, *73*, 724-739.

Simmons, F. B., & Beatty, D. L. (1962). A theory of middle ear muscle function at moderate sound levels. *Science*, *138*(3540), 590-592.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope*, *95*, 811-817.

Wiggers, H. C. (1937). The functions of the intra-aural muscles. *American Journal of Physiology*,*120*, 771-780.

Wilson, R.H. (1981). The effects of aging on the magnitude of the acoustic reflex. *Journal of Speech and Hearing Research*, *24*, 406-414.

Chapter 6

6 Summary, Implications, Strengths, Limitations and Future Directions

6.1 Summary

The foundation of this thesis was laid on growing evidence of auditory brainstem involvement in some children with suspected APD (Allen & Allan, 2007, 2014; Baina & Kraus, 2007; Gopal & Kowalski, 1999; Gopal & Pierel, 1999; Jisra, 2001; Linares & Carvallo, 2004; Meneguello et al., 2001; Muchnik et al., 2004; Sanches & Carvallo, 2006; Thomas, McMurry & Pillsbury, 1985). Previous studies reported a high percentage of abnormalities in acoustic reflexes of children with suspected APD (Allen & Allan, 2007, 2014; Meneguello et al., 2001; Thomas et al., 1985) but only some aspects of the reflex were measured. Despite the many reflex measures available for estimating auditory brainstem functioning via the acoustic reflex (thresholds, growth functions, latencies and decay), attention in the assessment of children with suspected APD was previously given only to reflex thresholds. Comparative data on acoustic reflex measures in typically developing children is rare and the results of reflex measures in children with clinical concerns are most often compared to that of normal hearing adults. Therefore the primary objectives of the thesis were to measure reflex thresholds, growth functions, latencies and decay in children with suspected APD and to compare those data from that obtained from both typically developing children and normal hearing adults. As well, a study of the functional consequences of acoustic reflex activation was explored via measurement of changes in absorbance and middle ear resonance.

Children with suspected APD included in this thesis were divided into two groups based on the diagnosis made using a clinically accepted, behavioral APD test battery. One group of clinical children was labeled as APD and included the children who received APD diagnosis on the basis of this battery. The other group, labeled clinical non-APD included children with clinical listening concerns who did not receive an APD diagnosis. This was done to compare the results of acoustic reflex measures with the diagnosis made using behavioral APD tests. Children in both clinical groups showed elevated threshold and shallower growth functions in contrast to typically developing children and normal hearing adults. Thresholds and growth functions were affected mainly in the crossed pathway. Although typically developing children had a tendency to show higher mean threshold when compared to adults, the effects were statistically similar when uncorrected for real ear differences. No statistical differences in reflex latency or decay were found between groups.

Clinically, thresholds are the most often used measure of the acoustic reflex. There are some reports of higher reflex thresholds in typically developing children in comparison to normal hearing adults (Jerger, Jerger & Mauldin, 1972; Jerger Hayes, Anthony & Mauldin, 1978; Osterhammel & Osterhammel; 1979) yet age-related norms are seldom applied. Study 1 of chapter 2 confirmed the observation that children tended to have slightly higher reflex thresholds when compared to adults although the results were not statistically significant. But ear canal volume and middle ear compliance are reported to develop till puberty (Abdala & Keefe, 2012; Obake, Tanaka, Hamada, Miura & Funai, 1988) and could affect the accurate measurement and interpretation of reflex threshold especially in children. In chapter 2, study 2, the effect of real ear correction for volume differences and middle ear compliance on reflex thresholds was investigated in children and adults. Typically developing children showed significantly higher thresholds than adults after the thresholds were corrected for ear canal volume differences. The relationship between static compliance and thresholds was strong in normal hearing adults which suggested the dependence of reflex threshold estimates on the compliance of the middle ear. No such relation was found in typically developing children. These results suggested that reflex thresholds in school aged children are not mature. Considering recent evidence of development in the auditory brainstem till 11 years (Skoe, Keizman, Anderson & Kraus, 2013), it is possible that higher reflex thresholds in children could be the result of neural development in the auditory brainstem.

Activation of acoustic reflex is suggested to modify functioning of the middle ear (Borg, 1968; Moller, 1958, 1965; Neergard, Anderden, Hansen & Jepsen, 1956; Nuttal, 1974; Simmons, 1959; Simmons, 1964; Wiggers , 1937). In chapter 5 we investigated the effect of reflex activation on middle ear functioning in normal hearing adults, typically developing children and children with suspected APD. We measured the effect of crossed reflex activation on middle ear function by measuring the change caused by its activation on middle ear absorbance and resonant frequency. It was found that following acoustic reflex activation, middle ear absorbance decreased between 226 and 1000 Hz, increased from 1000 and 2000 and was not affected above 2000 Hz. Changes in absorbance due to reflex activation were diminished and limited to only a few children in the suspected APD group. Comparison of maximum changes and differences in resonant frequency were, however, not significant between groups although individual differences were large. Overall, the effects of activation of acoustic reflex on middle ear absorbance and resonant frequency suggests that it transforms the middle ear to function like a high pass filter which can be critical in perception of speech in noise. Limited effects of acoustic reflex activation on middle ear absorbance and resonant frequency seen in some children with suspected APD point toward a restricted help in the perception of speech in the presence noise.

6.2 Implications

Abnormal acoustic reflexes were found in both clinical groups of children (APD and clinical non-APD). These results suggest: (1) Auditory brainstem involvement in APD is frequent and assessment of its functioning is important in children who are referred for auditory processing difficulties; (2) Children who did not receive an APD diagnosis based on behavioral APD, but showed abnormality in acoustic reflex measures, may have developed good cognitive and language skills allowing them to perform well on behavioral tests yet still experience listening difficulties in noise, possibly from their poor reflex functioning; and (3) Children who were diagnosed with APD based on behavioral APD tests and had abnormal acoustic reflex might have both poor auditory brainstem and cortical functioning. These results also suggested the inability of behavioral tests alone to diagnose APD if the deficit is limited to the auditory brainstem and good cognitive and language skills are in place. The results of this thesis indicate the importance of acoustic reflex testing in the assessment of APD and that measures beyond uncorrected thresholds be used. Clinical measurement of real ear corrected reflex thresholds and reflex growth functions are highly recommended in APD assessment. The use of reflex latencies and decay might have limited use in the assessment of this clinical population.

Acoustic reflex thresholds were found to be affected by characteristics of the peripheral system. Therefore those characteristics, especially ear canal volume and static compliance should be taken into account while making these measurements. Further it will be useful to compare results with normal data from individuals of similar age. Perhaps the development and use of acoustic reflex measures that would compensate for differences in peripheral hearing characteristics might be more effective.

The results of chapter 5 showed that some children with suspected APD, showed smaller effects of reflex activation on middle ear absorbance and resonant frequency, even when reflexes were present at normal threshold values. Understanding speech in presence of noise is the most common complaint in children with suspected APD and the result of study 4 suggest that this problem might be due the poor acoustic reflex activity in some children with suspected APD.

6.3 Strengths

- In all the studies, we compared acoustic reflexes of children with suspected APD with those of typically developing children of the same age.

- Children with suspected APD were divided into two groups based on the diagnosis made using a behavioral APD battery. This allowed better comparison of the findings of acoustic reflex measures with the diagnosis made using behavioral APD tests.

- Multiple aspects of the acoustic reflex were evaluated.

6.4 Limitations and future directions

- Threshold measurements in study 1 (Chapter 2) were made using 5 dB steps. The use of 1 dB step would take more time and could be uncomfortable for the participant but may provide more precise findings.

- In study 2 (Chapter 2), volume corrections were done only on uncrossed reflex thresholds. Similar correction for crossed reflex thresholds, if a different transducer is used, should be attempted in future studies. This will increase the effectiveness of reflex threshold measurements in clinical assessment.

- Listening in noisy environment is not limited to 15 seconds. But reflex decay was measured in chapter 4 for a stimulus presentation of only 15 seconds. Reflex decay over longer durations of stimulation should be measured in future studies.

- Abnormalities found in acoustic reflex measures and their physiologic impact on middle ear functioning in children with suspected APD was not compared with any behavioral speech in noise test. A future study should be directed to understand the relationship between abnormal acoustic reflexes and their physiologic impact on middle ear functioning with behavioral speech in noise difficulties in children with suspected APD.

6.5 References

Abdala, C., & Keefe, D. H. (2012). Morphological and functional ear development. In L. A. Werner, R. R Fay & A. N. Popper (Eds.), *Human Auditory Development* (pp. 19-59). New York: Springer.

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., Allan, C. 2014. Auditory Processing Disorders: relationship to cognitive processes and underlying auditory neural integrity. *International Journal of Paediatric Otorhinolaryngology*, 78, 198-208.

Banai, K., & Kraus, N. (2007). Neurobiology of (central) auditory processing disorder and language-based learning disability. In G. D. Chermak & F. E. Musiek (Eds.), Handbook of (central) auditory processing disorders (pp. 89{116). San Diego: Plural Publishing.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *Acta Oto-laryngologica, 66*, 461-472.

Banai, K., Nicol, T., Zecker, S., & Kraus, N. (2005). Brainstem timing: Implications for cortical processing and literacy. *Journal of Neuroscience, 25,* 9850–9857.

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.

Gopal, K.V. & Pierel, K. (1999). Binaural interaction component in children at risk for central auditory processing disorders. *Scandinavian Audiology*, 28, 77-84

Jerger, J., Hayes, D., Anthony, L. & Mauldin, L. (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Monographs in Contemporary Audiology*, *1*, 1-20.

Jerger, J., Jerger, S., & Mauldin, L. (1972). Studies in Impedance Audiometry: I. Normal and sensorineural ears. *Archives of Otolaryngolology*, *96*, 513-523.

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.

Liden, G., Nordlund, B., & Hawkins, J. E. (1964). Significance of the stapedius reflex for the understanding of speech. *Acta Oto-Laryngologica*, *57*(S188), 275-279.

Linares, A. E. & Carvallo, R. M. M. Acoustic reflex latency in children with auditory prossessing disorder. (2004). *International Archives of Otorhinolaryngology*. 8(1).

Meneguello, J., Domenico, M. L. D., Costa, M. C. M., Leonhardt, F. D., Barbosa, L. H. F., & Pereira, L. D. (2001). Occurrence of acoustic reflex changes in auditory processing disorders. *Brazilian Journal of Otorhinolaryngology*. 67 (7), 2001.

Møller, A. R. (1958). Intra-Aural muscle contraction in man, examined by measuring acoustic impedance of the ear. *The Laryngoscope*, *68*(1), 48-62.

Møller, A. R. (1965). An experimental study of the acoustic impedance of the middle ear and its transmission properties. *Acta oto-laryngologica*, *60*(1-6), 129-149.

Muchnik, C., Roth, D.A., Othman-Jebara, R., Putter-Katz, H., Shabtai, E.L. & Hildesheimer, M. (2004). Reduced medial olivocochlear bundle system function in children with auditory processing disorders. *Audiology & Neuro-Otology, 9*, 107-114. doi: 10.1159/000076001

Neergaard, E. B., Andersen, H. C., Hansen, C. C., & Jepsen, O. (1963). Experimental studies on sound transmission in the human ear. III. Influence of the stapedius and tensor sympani muscles. *Acta oto-laryngologica. Supplementum*, *188*, 280-286.

Nuttall, A. L. (1974). Tympanic muscle effects on middle-ear transfer characteristic. *The Journal of the Acoustical Society of America*, *56*(4), 1239-1247

Okabe, K., Tanaka, S., Hamada, H., Miura, T., & Funai, H. (1988). Acoustic impedance measurement on normal ears of children. *Journal of the Acoustical Society of Japan (E)*, *9*(6), 287-294.

Osterhammel, D., & Osterhammel, P. (1979). Age and sex variationsfor the normal stapedial reflex thresholds and tympanometric compliance values. *Scandinavian Audiology*, *8*, 153-158.

Sanches, S.G.G. & Carvallo, R.M. (2006). Contralateral suppression of transient evoked otoacoustic emissions in children with auditory processing disorder. *Audiology & Neurotology, 11*, 366-372.

Simmons, F. B. (1959). Middle ear muscle activity at moderate sound levels.*The Annals of otology, rhinology, and laryngology*, *68*, 1126.

Simmons, F. B. (1964). Perceptual theories of middle ear muscle function. *The Annals of otology, rhinology, and laryngology*, *73*, 724-739.

Thomas, W.G., McMurry, G. & Pillsbury, H.C. (1985). Acoustic reflex abnormalities in behaviorally disturbed and language delayed children. *Laryngoscope, 95*, 811-817.

Wiggers, H. C. (1937). The functions of the intra-aural muscles. *American Journal of Physiology*,*120*, 771-780.

Appendices

Appendix A: Ethics 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: 16505E
Review Level: Expedited
Review Date: September 30, 2009
Protocol Title: Testing the efficacy and efficiency of an improved comprehensive test battery for the assessment of auditory processing disorders.
Department and Institution: Health & Rehabilitation Sciences, University of Western Ontario
Sponsor: Ontario Research Fund
Ethics Approval Date: October 27, 2009
Expiry Date: December 31, 2014
Documents Reviewed and Approved: UWO Protocol, Letter of Information and Consent (LHSC Victoria Hospital), Letter of Information and Consent (UWO National Centre for Audiology)
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. Joseph Gilbert

Ethics Officer to Contact for Further Information

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

UWO HSREB Ethics Approval - Initial
V.2008-07-01 (rptApprovalNoticeHSREB_Initial)

16505E

cc: ORE File
LHRI

Page 1 of 1

Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Prudence Allen
Review Number: 16505E
Review Level: Delegated
Approved Local Participants: 180
Protocol Title: Testing the efficacy and efficiency of an improved comprehensive test battery for the assessment of auditory processing disorders.
Department & Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: Ontario Research fund

Ethics Approval Date: June 22, 2011 **Expiry Date:** December 31, 2014
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised UWO Protocol	Changes have been made to the test battery and letter of information in order to include a sub-group of normal hearing adults and children as a control/normal comparative group on acoustic reflex measures. Recruitment of these individuals will take place within the student population at Elborn College and through staff, family and friends associated with the NCA. A total of 50 individuals (25 children, 25 adults) will be recruited - this will not impact the sample size.	
Revised Letter of Information & Consent		
Assent		
Addition of Co-investigator	Udit Saxena has been added to the research team.	

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 revision(s) or amendment(s) 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.

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.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Signature

Ethics Officer to Contact for Further Information

The **University** *of* **Western Ontario**
Office of Research Ethics

[redacted]

LAWSON HEALTH RESEARCH INSTITUTE

FINAL APPROVAL NOTICE

RESEARCH OFFICE REVIEW NO.: R-09-503

PROJECT TITLE: Testing the efficacy and efficiency of an improved comprehensive test battery for the assessment of auditory processing disorders.

PRINCIPAL INVESTIGATOR: Dr. P Allen

DATE OF REVIEW BY CRIC: November 18, 2010

Health Sciences REB#: 16505E

Please be advised that the above project was reviewed by the Clinical Research Impact Committee and the project:

Was Approved

PLEASE INFORM THE APPROPRIATE NURSING UNITS, LABORATORIES, ETC. BEFORE STARTING THIS PROTOCOL. THE RESEARCH OFFICE NUMBER MUST BE USED WHEN COMMUNICATING WITH THESE AREAS.

V.P. Research
Lawson Health Research Institute

All future correspondence concerning this study should include the Research Office Review

cc: Administration

Western Research

Research Ethics

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Prudence Allen
File Number: 102932
Review Level: Delegated
Approved Local Adult Participants: 0
Approved Local Minor Participants: 480
Protocol Title: Auditory function and acoustic signal encoding in school-aged children
Department & Institution: Health Sciences\Communication Sciences & Disorders,Western University
Sponsor:
Ethics Approval Date: March 28, 2013 **Expiry Date:** December 30, 2014
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Letter of Information	102932 Letter of Information	
Assent	102932 Assent letter	

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 revision(s) or amendment(s) 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 University of Western Ontario Updated Approval Request Form.

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.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer to Contact for Further Information

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

Western University, Research, Support Services Bldg., Rm. 5150
[redacted]

Appendix B

Letter of Information and Consent

Western

Study: **Testing the efficacy and efficiency of an improved comprehensive test battery for the assessment of auditory processing disorders.**

Principal Investigator: Prudence Allen, Ph.D.

Co-Investigators: David Purcell, Ph.D.

Vijay Parsa, Ph.D.

Research Associates: Chris Allan, M.Sc.

Udit Saxena, M.Sc.

Place of testing: National Centre for Audiology, UWO

London Health Sciences Centre Victoria Hospital Campus

Assent for children

Why you are here?

This study is to help learn more about children with listening problems and the kinds of tests that can be used to discover those problems. Children with and without listening problems are being asked to be in the study. Dr. Allen and her research team are asking you to be part of this study so that they can learn more about how children listen and if the tests can help show who has listening problems.

Why are they doing this study?

They want to see how well you listen and if you are able to understand someone when they talk to you like when your teacher explains something or asks a question.

What will happen to you?

If you agree to be in the study you will be asked to visit the Child Hearing Research Laboratory for some hearing tests. This is what will happen when you come for your visit:

1. You will have your hearing tested. You wear earphones and raise your hand when you hear soft sounds and repeat some words that are said to you. This will only take a few minutes.
2. Some measurements will be made of your ears. To make these measurements an earplug will be used in your ear. You will not have to do anything but you will be asked to sit very still and not move your head or talk.

Will the study hurt?

You will not be wearing the earphones or earplugs long enough for them to hurt your ears. Some of the sounds used for the ear measurements are loud but they will not hurt.

Will you be a better listener if you get in the study?

This study won't make you a better or worse listener. The research team hopes that this study will help them understand how children listen so that in the future they can easily find which children will have listening problems and then be able to help teach them to be better listeners.

What if you have any questions?

You can ask questions any time, now or later. You can talk to anyone on the research team, your family or someone else.

Do you have to be in the study?

You don't have to be in the study. No one will be mad at you if you don't want to participate. If you don't want to be in the study just say so. Even if you say yes now, you can change your mind later. It's up to you.

Yes, I want to participate in this study

____
Print name of child

______________________ _____________________ _______________________
Signature of child Age Date

_____________________________ _______________________
Signature of person obtaining consent Date

Letter of Information and Consent

UWO National Centre for Audiology

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Prudence Allen, Ph.D.
Co-Investigator: Vijay Parsa, Ph.D.
Co-Investigator: David Purcell, Ph.D.
Research Associate: Chris Allan, M.Sc.
Udit Saxena, M.Sc
Place of testing: National Centre for Audiology, UWO

Dear Potential Participant,

The pronouns “you” and “your” should be read as referring to the participant rather than the parent/guardian/next-of-kin who is signing the consent form for the participant.

This letter contains information to help you decide whether or not to participate in this research. It is important for you to know why the data is being collected and the research is being conducted and what we are asking you to agree to. Please take time to read this carefully and feel free to ask questions if anything is unclear.

<u>Description and Purpose of the Research Project:</u>

You are being invited to participate, as part of a normal comparison group, in a study of hearing and auditory processing (listening) taking place at Elborn College in the University of Western Ontario. Auditory processing refers to those listening abilities that allow us to understand speech when it is unclear (muffled) or when we are trying to listen to someone and the room is noisy. This project has been planned to investigate the usefulness of a handheld computer system and several different tests in the assessment of various auditory skills. We plan to compare the performance of normal or typically developing individuals with those suspected of having or diagnosed as having an auditory processing deficit. In total there will be approximately 825 children and 75 adults participating in this research study.

One objective of this project is to investigate eardrum and middle ear function in children and adults. The assessment of eardrum and middle ear function is a routine test that is conducted during hearing assessments. This research project is attempting to determine if the test results can provide information about auditory function that may be helpful in identifying young children that have listening problems.

If you agree to participate in this part of the project, you will be asked to sit comfortably in a soundproof or quiet room listening to different sounds while wearing earphones. Several measurements will be made to test your eardrum function. During these measurements you will be asked to sit quietly because you do not have to respond to any of the sounds you hear. The auditory equipment will make all of the ear measurements.

Test sessions will last no longer than 45 minutes and will be scheduled for your convenience. Free parking will be provided for the study.

Benefits and Risks:

This study will involve no known risk to you. The sounds you will be hearing will never be so loud as to be 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 upon request.

<u>Protection of Your Privacy</u>:

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 unique ID code will be used to reference each participant, rather then their full names. ID codes and corresponding full names of participants will be kept in a journal and locked in a cabinet. Information collected on the handheld device or computer will be password protected and locked in a cabinet when not in use, to ensure it remains confidential at all times. Only the local research team may have access to the cabinet. 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 and personal information 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 age group only.

<u>Participation in the Study</u>:

Participation in the study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time. You can withdraw your data from inclusion in the study up until the data collection process is complete. At that point, all personal information will have been destroyed, leaving the IDs and linked data anonymous so it will no longer be possible to identify and remove your data from the study.

<u>Contacts for Questions about the Research Project</u>:

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.

This letter is yours to keep.

When you attend the data collection appointment, the letter of information will be reviewed with you, any lingering questions will be answered and if you choose to participate we will then complete the consent form. You will receive a copy of the signed consent form at that time.

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

Sincerely,
Prudence Allen

CONSENT FORM

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Dr. Prudence Allen, Associate Professor
National Centre for Audiology
University of Western Ontario,

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

 I agree to participate OR I do not agree to participate

Name of participant (Print)

-- --------------------------
Signature of participant Date

Name of legally authorized representative (Print)

-- --------------------------
Signature of legally authorized representative Date

Name of person obtaining consent (Print)

--   ---------------------------

Signature of person obtaining consent   Date

Letter of Information and Consent

LHSC, Victoria Hospital

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Prudence Allen, Ph.D.
Co-Investigator: Vijay Parsa, Ph.D.
Co-Investigator: David Purcell, Ph.D.
Research Associate: Chris Allan, M.Sc.
Place of testing: LHSC, Victoria Hospital ENT & Audiology Department

General Information:

The pronouns "you" and "your" should be read as referring to the participant rather than the parent/guardian/next-of-kin who is signing the consent form for the participant.

This letter contains information to help you decide whether or not to participate in this research. It is important for you to know why the data is being collected and the research is being conducted and what we are asking you to agree to. Please take time to read this carefully and feel free to ask questions if anything is unclear. If you have any questions let the receptionist know and someone will speak with you directly.

During the course of your treatment in the ENT & Audiology Department at LHSC Victoria Hospital, you will have a number of tests and treatments done as part of your regular care and a great deal of information about your past and current medical history will also be collected. This is all done as part of your standard care to help us determine how well you can hear and listen and how best to treat you if necessary.

Description and Purpose of the Research Project:

The physicians and staff in the ENT & Audiology Department at LHSC Victoria Hospital are engaged in ongoing research to better understand hearing and auditory processing difficulties and how best to treat these problems. We are asking for your permission to collect and use the information from your health record, for research purposes. All patients who attend our clinic will be asked to participate. One objective of this project is to investigate, in children and adults, the usefulness of a computer system in the assessment of various auditory skills such as the presence of a very brief sound or the ability to distinguish a change in the pitch, loudness, or quality of a sound. This hearing measurement device is available in a laptop as well as a handheld version and has been developed with new digital and wireless technology that has only recently become available. The auditory skills that can be assessed by these devices are ones that up until now have only been tested in research laboratories, like the University of Western Ontario Child Hearing Research Lab, because the older equipment was too large and expensive to operate in hospitals or audiology clinics. If this new device is proven to accurately measure auditory skills then, it is the intention of the researchers to commercialize the device by establishing a company for the manufacturing and sale of the device or license the software to other companies, so that the opportunity to better assess and treat hearing disorders can be moved into audiology clinics.

Protection of Your Privacy:

If you agree to participate, data relating to your health history and current care will be copied from your hospital records to a separate research database. All identifying information such as your name, address and OHIP number will be removed. The information in the research database will be identified by a unique code number that will link the test results in the research record. The master list that contains the link to the code number and your name and other identifying information will be kept in a very secure location at the University of Western Ontario under the control of the Director of the research. The research database will be owned by the University of Western Ontario National Centre for Audiology and it will be stored in a secure location on the University of Western Ontario National Centre for Audiology computer system. The data in the research database will be kept as it is being collected and analyzed. Once the project is completed, all information containing participants' names and unique codes, including backup DVD's and paper documents, will be deleted and overwritten or destroyed by shredding.

If the results of the research are published or presented at scientific meetings, your name will not be used and no information that discloses your identity will be released or published without your explicit consent. Only group data will be reported and if individual data is reported, references will be made to the age group only.

Participation in the Study:

Participation in this study is voluntary. You may refuse to participate, or refuse to allow data to go to the research the database at any time with no effect on your future care.

Information that has already been transferred to the research database can be withdrawn from the study up until the data collection process is complete. At that point, all personal information will have been destroyed, leaving the unique code number and linked data anonymous so it will no longer be possible to identify and remove your data from the study. If you wish to stop your participation just let the staff at the clinic know.

Regardless of your decision to participate you can still receive continuing care through this clinic. You do not waive any legal rights by signing the consent form.

The database will also help us to identify those patients who may be eligible to participate in future research projects that involve more that just an analysis of existing data. In the future you may be approached to participate in other research projects in the clinic. In those instances you will be given detailed information describing the project and you will have the opportunity to decide at that time, whether or not you want to participate in the new project.

Benefits and Risks:

You will not be compensated for your participation in this database.

The only known risk to your participation in this study is the possibility that, because the research database is linked to our clinical database, someone may be able to identify you. However the research database is secured in the same manner as our clinical records and access is limited to authorized personnel only.

You will not benefit directly from participation in this research however the results of our research may help other patients in the future who suffer from problems similar to yours.

Contacts for Questions about the Research Project:

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.

If you have any questions about the research or the database you may contact Dr. Prudence Allen. If you have any questions about your participation in the study or the testing that you completed you can contact Chris Allan
If you have any questions about your ongoing follow-up at the hospital you can contact Denise Lewis in the Victoria Hospital Audiology Department.

If you have any questions about your rights as a research participant or the conduct of the study you may contact Dr. David Hill, Scientific Director, Lawson Health Research Institute.

This letter is for you to keep.
You will also be given a copy of the consent form if you agree to sign it.

Prudence Allen

CONSENT FORM

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Dr. Prudence Allen, Associate Professor
National Centre for Audiology
University of Western Ontario,

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

☐ I agree to participate OR ☐ I do not agree to participate

Name of participant (Print)

---   ---------------------------
Signature of participant   Date

Name of legally authorized representative (Print)

--- ---------------------------

Signature of legally authorized representative Date

Name of person obtaining consent (Print)

--- ---------------------------

Signature of person obtaining consent Date

Western
Health Sciences

Letter of Information and Consent

UWO National Centre for Audiology

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Prudence Allen, Ph.D.
Co-Investigator: Vijay Parsa, Ph.D.
Co-Investigator: David Purcell, Ph.D.
Research Associate: Udit Saxena, M.Sc.
Chris Allan, M.Sc.
Place of testing: National Centre for Audiology, UWO

Dear Potential Participant,

The pronouns “you” and “your” should be read as referring to the participant rather than the parent/guardian/next-of-kin who is signing the consent form for the participant.

This letter contains information to help you decide whether or not to participate in this research. It is important for you to know why the data is being collected and the research is being conducted and what we are asking you to agree to. Please take time to read this carefully and feel free to ask questions if anything is unclear.

Description and Purpose of the Research Project:

You are being invited to participate in a study of hearing and auditory processing (listening) taking place at Elborn College in the University of Western Ontario. Auditory processing refers to those listening abilities that allow us to understand speech when it is unclear (muffled) or when we are trying to listen to someone and the room is noisy. This project has been planned to investigate the usefulness of a handheld computer system and several different tests in the assessment of various auditory skills. We plan to compare the performance of normal or typically developing individuals with those suspected of having or diagnosed as having an auditory processing deficit. In total there will be approximately 825 children and 75 adults participating in this research study.

One objective of this project is to investigate, in children and adults, the usefulness of a computer system in the assessment of various auditory skills such as the presence of a very brief sound or the ability to distinguish a change in the pitch, loudness, or quality of a sound. This hearing measurement device is available in a laptop as well as a handheld version and has been developed with new digital and wireless technology that has only recently become available. The auditory skills that can be assessed by these devices are ones that up until now have only been tested in research laboratories, like the Child Hearing Research Lab, because the older equipment was too large and expensive to operate in hospitals or audiology clinics. If this new device is proven to accurately measure auditory skills then, it is the intention of the researchers to commercialize the device by establishing a company for the manufacturing and sale of the device or license the software to other companies, so that the opportunity to better assess and treat hearing disorders can be moved into audiology clinics.

If you agree to participate, you will be asked to sit comfortably in a soundproof or quiet room listening to different sounds while wearing earphones. You will be asked to repeat words or report what sounds they have heard. You will also complete listening tasks that involve watching a regular size computer screen or handheld computer screen. You will be presented with three colourful cartoon graphics and with each cartoon appearance on the screen you will hear 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 regular-size touch-screen monitor or by touching the graphic with a stylus on the handheld system. The responses will be recorded by the computer.

Test sessions will last no longer than 2.5 hours (scheduled for your convenience) and testing may be divided into several sessions at your request. Free parking will be provided for the study.

Benefits and Risks:

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.

Protection of Your Privacy:

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 unique ID code will be used to reference each participant, rather then their full names. ID codes and corresponding full names of participants will be kept in a journal and locked in a cabinet. Information collected on the handheld device or computer will be password protected and locked in a cabinet when not in use, to ensure it remains confidential at all times. Only the local research team may have access to the cabinet. 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 and personal information 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 age group only.

<u>Participation in the Study</u>:

Participation in the study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time. You can withdraw your data from inclusion in the study up until the data collection process is complete. At that point, all personal information will have been destroyed, leaving the IDs and linked data anonymous so it will no longer be possible to identify and remove your data from the study.

<u>Contacts for Questions about the Research Project</u>:

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.

This letter is yours to keep.

When you attend the data collection appointment, the letter of information will be reviewed with you, any lingering questions will be answered and if you choose to participate we will then complete the consent form. You will receive a copy of the signed consent form at that time.

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

Sincerely,

Prudence Allen

CONSENT FORM

Study: Comprehensive assessment of auditory processing (listening) abilities

Principal Investigator: Dr. Prudence Allen, Associate Professor
National Centre for Audiology
University of Western Ontario,

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

☐ I agree to participate OR ☐ I do not agree to participate

Name of participant (Print)

--- --------------------------

Signature of participant Date

Name of legally authorized representative (Print)

--- --------------------------

Signature of legally authorized representative Date

Name of person obtaining consent (Print)

-- --------------------------

Signature of person obtaining consent Date

Auditory function and acoustic signal encoding in school-aged children

CONSENT FORM

I have read the accompanying Letter of Information. The nature of the study has been explained to meand I agree to participate in this study.

All questions have been answered to my satisfaction.

Date: ____

Name:____

Signature:____

Did you experience any reading or learning difficulties while attending school? ☐ YES ☐ NO

Name of person obtaining informed consent:____

Signature of person obtaining informed consent:_____________________________________

Study: **Auditory function and acoustic signal encoding in school-aged children**

Principal Investigator: Prudence Allen, Ph.D.

Research Associates: Chris Allan, M.Sc.

Udit Saxena, M.Sc.

Moumita Choudhury, M.Sc.

Place of testing: London Children's Connection Childcare Centre

Assent for children ages 7 to 13 years

Why are you here?

This study is to help learn more about children's hearing and listening abilities and the kinds of tests that can be used to discover listening problems. Children with and without listening problems are being asked to be in the study. Dr. Allen and her research team are asking you to be part of this study so that they can learn more about how children listen and if the tests can help show who has listening problems.

Why are they doing this study?

They want to see how well you listen and if you are able to understand someone when they talk to you like when your teacher explains something or asks a question.

What will happen to you?

If you agree to be in the study you will be asked to do some hearing tests after school while you are waiting for your parents. This is what will happen when you see someone from the research team:

1. You will have your hearing tested. You wear earphones and raise your hand when you hear soft sounds. This will only take a few minutes.
2. Some measurements will be made of your ears. To make these measurements an earplug will be used in your ear. You will not have to do anything but you will be asked to sit very still and not move your head or talk.
3. You will play some listening games on the computer. When you play these easy games you will be wearing earphones so you can hear the sounds. The games do not take long, only a few minutes, but you may not want to finish all of them on one day.

Will the study hurt?

You will not be wearing the earphones or earplugs long enough for them to hurt your ears. Some of the sounds used for the ear measurements are loud but they will not hurt.

Will you be a better listener if you get in the study?

This study won't make you a better or worse listener. The research team hopes that this study will help them understand how children listen so that in the future they can easily find which children will have listening problems and then be able to help teach them to be better listeners.

What if you have any questions?

You can ask questions any time, now or later. You can talk to anyone on the research team, your family or someone else.

Do you have to be in the study?

You don't have to be in the study. No one will be mad at you if you don't want to participate. If you don't want to be in the study just say so. Even if you say yes now, you can change your mind later. It's up to you.

☐ Yes, I want to participate in this study

____
Print name of child

______________________ _____________________ _______________________
Signature of child Age Date

_____________________________ _______________________
Signature of person obtaining consent Date

Western
Health Sciences

Letter of Information and Consent

Study: Auditory function and acoustic signal encoding in school-aged children.

Principal Investigator: Prudence Allen, Ph.D.
Research Associates: Chris Allan, Ph.D.
Udit Saxena, M.Sc.
Moumita Choudhury, M.Sc.

Place of testing: London Children's Connection - School Age Program

Dear Potential Participant,

The pronouns "you" and "your" should be read as referring to the participant rather than the parent/guardian/next-of-kin who is signing the consent form for the participant.

Normal hearing and good auditory processing (listening) abilities are necessary for children to experience success in school. Recent studies have shown that some children experiencing school failure have Auditory Processing Disorders.

Auditory processing disorders have also been found in children that experience difficulty learning to read and/or have delays in their speech development. You are being invited to participate in a study of hearing and listening being conducted by Western's Child Hearing Research Laboratory. This study is investigating the usefulness of various listening tests, such as the ability to distinguish a change in pitch, loudness or quality of a sound. The performance of normal or typically developing children will be compared to children with auditory processing disorders.

Participants Initials ________

The objective of this project is to investigate hearing and listening abilities in children so that assessment tools can be developed for early and accurate identification of children with listening problems. In this study we plan to compare the performance of typically developing children with that of children with known Auditory Processing Disorders. For both groups of children, participants between the ages of 4 to 17 years old will be included in this study.

Ear and hearing measurements

This research project has been discussed with London Children's Connection administrators and Board of Directors. They have agreed to allow for the distribution of this letter and for your convenience, they have given permission for the testing to take place during the after-school program. If you agree to participate, one of the program staff will bring you to a quiet room where the researchers have set-up all of their computers and ear-measurement equipment. You will sit comfortably with the program staff and researchers in a quiet room, listening to different sounds while wearing earphones. The listening tasks are completed by listening to sounds while watching a regular size computer screen or handheld computer screen. You will be presented with child-friendly computer graphics and with each graphic appearance on the screen you will hear a sound. You will be asked to identify which graphic on the computer screen best corresponds to what was just heard. The responses will be recorded by the computer.

We will also be making some measurements of your ears. During these tests you will wear earplugs and you will hear a variety of different sounds. Some of the sounds will be loud but they are not harmful. You can relax during these tests because you are not required to do anything other than remain still. Each test, individually, only takes a few minutes to complete but in total there is about 1.5 hours of testing to be completed.

Test sessions will be arranged so that they do not interfere with the London Children's

Participants Initials ________

Connection - School Age Program. They will also be short and last no longer than 20 minutes to help promote attention and focus on the task. Most children will be seen over 3 – 6 sessions in order to complete all of the test measures. Once the testing has started it should be completed in 3 – 4 weeks.

Study risks

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.

Privacy and confidentiality

The information gathered during this study will remain confidential at all times. Information collected at the program on the computers will be password protected to ensure it remains 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 unique 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 at Western. Only the local research team may have access to the cabinet. 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 and personal information 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

Participants Initials ________

data will be reported. If individual data is reported, references will be made to the age group only.

Voluntary participation

Participation in the study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time. You can withdraw your data from inclusion in the study up until the data collection process for the study is complete. At that point, all personal information will have been destroyed, leaving the IDs and linked data anonymous so it will no longer be possible to identify and remove your data from the study.

Contact information

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 questions at any time you may contact me at the above address or at the following phone number: You can also speak to the research audiologist, if you have any questions or concerns about the study. If you have any questions about the conduct of this study or your rights as a research subject you may contact the Office of Research Ethics, The University of Western Ontario, email at: Thank you for your time and consideration.

Sincerely,

Dr. Prudence Allen, Ph.D.

Curriculum Vitae

Name:	Udit Saxena
Post-secondary Education and Degrees:	All India Institute of Speech and Hearing Mysore, Karnataka, India 2004-2008 B.Sc All India Institute of Speech and Hearing Mysore, Karnataka, India 2008-2010 M.Sc The University of Western Ontario London, Ontario, Canada 2011-present PhD candidate.
Honours and Awards:	Student Poster Outstanding Research Award (2013) by Canadian Academy of Audiology Travel award (2013) Faculty of Health Sciences and Health & Rehabilitation Sciences, Western University, 2013.
Related Work Experience:	Teaching Assistant The University of Western Ontario London, Ontario, Canada 2011-2014 Audiologist Grade I King George Medical College Lucknow, Uttar Pradesh, India. 2010-2010.

Selected Presentations:

Saxena U, Allan C, & Allen P. (2014). Crossed and uncrossed acoustic reflex latencies in normal hearing adults, typically children and children with suspected auditory processing disorders (Poster). Association for research in otorhynolaryngology mid winter meeting, SanDiego, USA.

Saxena, U., Allan, C., & Allen, P. (2013). Crossed and uncrossed acoustic reflex growth functions in normal hearing adults, typically developing children and children with suspected auditory processing disorders (Poster). Canadian Academy of Audiology annual conference, Newfounland and Labrador, Canada.

Saxena, U., Allan, C., & Allen, P. (2013). Crossed and uncrossed acoustic reflex growth functions in normal hearing adults, typically developing children and children with suspected auditory processing disorders (Poster). Association for research in otorhynolaryngology mid winter meeting, Baltimore, USA.

Saxena U, Tripathy R, Rajalakshmi KR (2009). The role of efferent auditory system in temporal processing in different age groups (Platform). National Symposium on Acoustics, Madras-India Chapter of the Acoustic Society of America, Hyderabad, India.

Saxena U, Tripathy R, Rajalakshmi KR (2010). Electrophysiologic evaluation of the effect of the background noise on sound prosessing in children and adults (Platform). 42nd annual convention of the Indian Speech & Hearing Association conference, Bangalore, India.

Tripathy R, **Saxena U**, Rajalakshmi KR (2009). Objective evaluation of temporal processing in normal hearing children and children with learning disability (Platform). 42ND annual convention of the Indian Speech & Hearing Association conference, Bangalore, India.

Saxena U, Roy I, Rajalakshmi KR (2007). Auditory localization abilities in normal hearing children and children with hearing loss (Poster). 39th annual convention of the Indian Speech & Hearing Association, Calicut, India.

Roy, I, **Saxena, U**, Goswami, SP (2007) Autism: Access and Practice. (Poster). 39th annual convention of the Indian Speech & Hearing Association, Calicut, India.