STIMULUS RATE AND SUBCORTICAL AUDITORY PROCESSING OF SPEECH: COMPARISON BETWEEN YOUNGER AND OLDER ADULTS

Garvita
Register No. 10AUD012

A Dissertation Submitted in Part Fulfillment of Final Year
Master of Science (Audiology)
University of Mysore, Mysore

All India Institute of Speech and Hearing
Manasagangothri, Mysore-570006
May 2012

“DEDICATED TO MY MOTHER, FATHER, BHAIYA, BHABHI AND MY GUIDE”

CERTIFICATE

This is to certify that this dissertation entitled **"Stimulus Rate and Subcortical Auditory Processing of Speech: Comparison between younger and older adults"** is the bonafide work submitted in part fulfillment for the Degree of Master of Science (Audiology) of the student with Registration No.: 10AUD012. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Dr. S. R. Savithri
Director
All India Institute of Speech and Hearing,
Manasagangothri, Mysore- 570006

Mysore
May, 2012

CERTIFICATE

This is to certify that this dissertation entitled **"Stimulus Rate and Subcortical Auditory Processing of Speech: Comparison between younger and older adults"** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier in other University for the award of any Diploma or Degree.

Mr. Sujeet Kumar Sinha
Guide
Lecturer in Audiology,
Department of Audiology,
All India Institute of Speech and Hearing,
Manasagangothri, Mysore- 570006

Mysore
May, 2012

DECLARATION

This is to certify that this Master's dissertation entitled "**Stimulus Rate and Subcortical Auditory Processing of Speech: Comparison between younger and older adults**" is the result of my own study under the guidance of Mr. Sujit Kumar Sinha, Lecturer in Audiology, Depertment of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier in other University for the award of any Diploma or Degree.

Mysore Register No. 10AUD012

May, 2012

Acknowledgement

I am grateful to my beloved Lord for having considered me worthy of this life. God, you have been the guiding force for me in everything that I have done. You have carried me through happiness and sorrow, leisure and work, rain and sun in a manner that I have always wondered how. But I know, it is always You. Thank You…

My Mummy and Papa, you both are so very special to me that I can never even attempt to thank you. You have been with me, known me, cared for me every day, every single moment. You have loved me in your own special way. You are my biggest strength. I feel so blessed to be called myself as your daughter.

My Garvit Bhaiya, you are so precious to me. You mean the world to me. Bhaiya, you are my strength when am low. It is wonderful how you hold me when I tend to fall. All these years, I may not have stayed home but the bond between us has always been strong. Only a heart as dear as yours would give me so unselfishly. Richly blessed is how I feel to have a Brother like you.

My Aditi Bhabhi, a new member added to my family. Welcoming you dear Bhabhi. You have filled my life with love and compassion. You are a blessing to our family. Love you.

My sincere and heartfelt thanks to my teacher, my guide Mr. Sujeet Kumar Sinha, who has been instrumental in the completion of this dissertation. This work would not have been possible without your encouragement, expertise, skillful guidance and zeal for perfection. Sir, I am ever grateful to you for your trust and confidence on me. Your patience and dedication to work and research never failed to amaze me. Your words, your guidance will remain with me throughout my life.

I would like to thank Dr. S. R. Savithri, Director, All India Institute of Speech and Hearing, Mysore, for permitting me to carry out this study.

I would like to thank the HOD, Department of Audiology, Ms. Manjula P., for permitting me to use the test equipments to conduct the study.

I would like to thank Ms. Vasathalakshmi for her help in statistical analysis and for her valuable suggestions.

I am grateful to my teacher, Mr. Sandeep M., who has moulded me into this field. Your guidance, teaching has generated my interest into the field of Audiology. You have always let me explore and learn. Your words are extremely powerful. Thank you for being my teacher.

I would like to thank Hemath Sir, Ganapathy Sir, Prashanth Sir, Arun Raj Sir, Anthony Sir, for helping me out in my data collection. You are the sole reason that I finished my data collection in time.

I would like to thank the faculty members of the library for their unending support.

I thank all my teachers from my first year at AIISH till date, for motivating me to deepen my knowledge in Speech and Hearing.

Srishti Rawat, you are the best pal one can ever have. You have always been there for me to support me in all my endeavors. You were always there to release all my tensions, worries and to guide me to move ahead. Though I know you from just one year, but every moment of our togetherness is a memory to be cherished forever. May God bestow you with all the happiness and success in the world.

I would like to thank my seniors Mr. Nike Gnanateja and Mr. Ranjit Ranjan for all their support and guidance.

I would like to thank my juniors Laxmidevi, Vidyalaxmi, Shruti Sahani, Anchala, Sneha B, Kumari Nisha, Margaret, Tannaz, Vishnu Priya, Kirthi, Varsha, Rashika Sharma, Nainitha K, Pooja, Divya, Sarga, Amrutha for becoming the participants of the study.

I am also very thankful to Mr. Shivaswamy, Mr. Gururaj, Mr. Mahadevamma, Mr. S. Kumar, Mr. Nagendra, Mr. Dinesh, Mr. Mahesh, Mr. Abdul Azeez, Gayathri akka, Puttakka to take out their valuable time and to agree to become the participants for the conduction of the study.

I thank everyone, I thank this place, the All India Institute of Speech and Hearing, Mysore for making me feel so belonged to this place. I thank AIISH for the great friends I made, great people I met, great teachers who taught me and moulded me into a person I am today.

TABLE OF CONTENTS

Chapter	Title	Page No.
1	Introduction	1-5
2	Review of Literature	6- 27
3	Method	28- 37
4	Results	38- 65
5	Discussion	66- 74
6	Summary and Conclusion	75- 79
	References	80- 95

LIST OF TABLES

Table No.	Title	Page No.
Table 3.1	Parameters used to record click and speech evoked ABR	33
Table 4.1	Mean and Standard deviation (SD) of click evoked ABR wave V latency obtained at three repetition rates across the groups	40
Table 4.2	Bonferroni Post Hoc Test results for the wave V latency of the click evoked ABR across the three repetition rates	40
Table 4.3	Bonferroni Post Hoc Test results for the wave V latency of the click evoked ABR at the three repetition rates across the groups	41
Table 4.4	Mean and Standard deviation (SD) of different speech evoked ABR latencies obtained at three repetition rates across the groups	43
Table 4.5	Bonferroni Pairwise Comparison results for /da/ evoked speech ABR across the three repetition rates	44
Table 4.6	Bonferroni Post Hoc Test results for the /da/ evoked wave V and A latency at the three repetition rates for young and older adult age group.	45
Table 4.7	Bonferroni Post Hoc Test results for the /da/ evoked wave D latency at the three repetition rates for young and older adult age group.	46
Table 4.8	Bonferroni Post Hoc Test results for the /da/ evoked wave E latency at the three repetition rates for young and older adult age group.	47

Table 4.9	Bonferroni Post Hoc Test results for the /da/ evoked wave F latency at the three repetition rates for young and older adult age group.	48
Table 4.10	Mean and Standard deviation (SD) of F0, F1 and F2 amplitude elicited by syllable /da/ obtained at three repetition rates across the groups	50
Table 4.11	Bonferroni Pair Wise Comparison results for the amplitude of F0, F1 and F2 of /da/ evoked ABR across the three repetition rates.	51
Table 4.12	Bonferroni Post Hoc Test results for the /da/ evoked F0 amplitude across the three repetition rates for young age group.	52
Table 4.13	Bonferroni Post Hoc Test results for the /da/ evoked F1 amplitude across the three repetition rates for young age group	52
Table 4.14	Bonferroni Post Hoc Test results for the /da/ evoked F2 amplitude across the three repetition rates for young and older adult age group.	53

LIST OF FIGURES

Figure No.	Title	Page No.
Figure 2.1	Average 10-year longitudinal changes in pure-tone hearing level (HL) thresholds across frequency for **(a)** men and **(b)** women.	7
Figure 2.2	Mean pure-tone air conduction thresholds for (a) men and (b) women in four age groups.	8
Figure 2.3	Stimulus waveform of /da/ and a representative response waveform.	15
Figure 3.1	Mean and the standard deviation of the thresholds at the octave frequencies for the young and older adult age group	28
Figure 3.2	Spectral and temporal aspects of the speech stimulus /da/	31
Figure 3.3	A representative waveform of click evoked ABR having replicable peaks at 9.1 /s, 19.1/s, and 40.1 /s respectively.	34
Figure 3.4	A representative waveform of speech evoked ABR having replicable peaks at 6.9/s, 10.9/s, and 15.4/s respectively.	35
Figure 3.5	FFT representing the energies at fundamental and its harmonics.	37
Figure 4.1	A sample waveform of click evoked ABR recorded at three different repetition rates in a young adult.	39

Figure 4.2	A sample waveform of Speech evoked ABR- transient and FFR waveform at three repetition rates obtained from one young group individual.	42
Figure 4.3	Mean latency of wave V peak latency of click ABR for three repetition rates across the two groups.	54
Figure 4.4	Latency of speech evoked transient V peak latency for three repetition rates across the two groups.	55
Figure 4.5	Latency of speech evoked transient A peak latency for three repetition rates across the two groups.	56
Figure 4.6	Latency of speech evoked D peak latency for three repetition rates across the two groups.	57
Figure 4.7	Latency of speech evoked E peak latency for three repetition rates across the two groups.	58
Figure 4.8	Latency of speech evoked F peak latency for three repetition rates across the two groups.	59
Figure 4.9	Amplitude of F0 at 6.9, 10.9 and 15.4 repetition rates across the two groups.	60
Figure 4.10	Amplitude of F1 at 6.9, 10.9 and 15.4 repetition rates across the two groups.	61
Figure 4.11	Amplitude of F2 at 6.9, 10.9 and 15.4 repetition rates across the two groups.	62
Figure 4.12	Correlation analysis between the age and the latency of the frequency following responses (sustained responses)	64

Chapter- 1

Introduction

Older aged individuals have been shown to have greater difficulty with speech understanding than younger listeners (CHABA, 1988). The difficulty in understanding speech in elderly listeners had been attributed primarily to a high frequency sensorineural hearing loss. However, there are studies which demonstrate that in adverse listening conditions, in older individuals with essentially normal peripheral hearing sensitivity, have difficulty in understanding speech (Ewertsen & Birk-Nielsen, 1971; Plomp & Mimpen, 1979; Nabelek & Robinson, 1982; Era, Jokela, Qvarnberg & Heikkinen, 1986; Gelfand, Piper & Silman,1986; Dubno, Horwitz & Ahlstrom, 2002; Kim, Frisina, Mapes, Hickman & Frisina, 2006; Wingfield, McCoy, Peelle, Tun & Cox, 2006). This may lead one to conclude that age-related changes occur beyond the peripheral auditory system, i.e., the central auditory nervous system (CANS) might play a role in this difficulty (Gordon-Salant, 1987; Humes, 1996; Frisina & Frisina, 1997; Mazelova, Popelar & Syka, 2003).

One of the most important noticeable aspects in most of these studies is the age range of the subjects who participated for these studies. These studies have a group of subjects in the middle age range i.e. in the age range of 40-60 years (Ewertsen & Birk-Nielsen, 1971; Plomp & Mimpen, 1979; Nabelek & Robinson, 1982; Era et al, 1986; Gelfand et al., 1986; Kim et al. 2006). There are some other research studies which also suggest that certain auditory abilities begin to decline in older adults. For example, Barr and Giambra (1990) reported that middle-aged subjects perform more poorly than younger listeners (but better than older individuals) on tasks such as perception of dichotically presented speech. Bergman (1971) reported a significant decline in perception of interrupted speech in middle aged individuals, whereas Vaughnan and Letowski (1997) reported a significant decline in understanding of time-compressed speech in older adults compared to the young individuals.

Thus, it is clear that the older adults with normal hearing may have a decline in understanding speech in adverse listening conditions, although this decline may be lesser compare to the older individuals. As we understand that the difficulty in speech understanding in older individuals arises from the central auditory nervous system, the decline of speech understanding in older adults also may arise from the central auditory nervous system itself. One form of central auditory processing that has been attributed to part of this difficulty in older individuals is the temporal processing (Fitzgibbon & Gordon-Salant, 1996; Strouse, Ashmead, Ohde & Grantham, 1998; Gordon-Salant & Fitzgibbon, 1999; Schneider & Pichora-Fuller, 2000; Pichora-Fuller, 2003; Pichora-Fuller & Souza, 2003; Fogerty, Humes & Kewley-Port, 2010). Thus, it may be hypothesized that some of the difficulties in understanding speech in the adverse listening conditions in older adults also, may be arising from difficulty in temporal processing.

Temporal refers to time-related aspects of the acoustic signal. Temporal processing is critical to a wide variety of everyday listening tasks, including speech perception and perception of music (Hirsh, 1959). Temporal processing is one of the functions necessary for the discrimination of subtle cues such as voicing and discrimination of similar words. Auditory temporal processing is not a unitary construct and the temporal phenomena present in acoustic stimuli manifest themselves in different ways depending on the task (Green, 1984) and is also based on the relevant timescales and the presumed underlying neural mechanisms. According to Klein (2002), temporal processing deficits could involve a hierarchy of temporal information-processing functions ranging from the perception and identification of stimuli to individualizing and perceiving multiple stimuli presented in the correct sequences.

One way to assess the temporal processing electrophysiologically is to study the stimulus complexity by examining the effects of stimulus rate on speech evoked auditory brainstem responses (Krizman, Skoe & Kraus, 2010; Basu, Krishnan & Weber-Fox, 2010). Recently Speech evoked auditory brainstem responses (sABR) measures have been introduced as a means to study the brainstem encoding of speech sounds (Russo, Nicol, Mussacchia & Kraus, 2004; Banai, Nicol, Zecker & Kraus, 2005; Sinha & Basavaraj, 2010a; Sinha & Basavaraj, 2010b). Speech evoked ABR waveforms comprises of onset response and sustained peaks which is also known as the frequency-following response (FFR). FFR is a steady state AEP that is sensitive to sustained features within a stimulus and is dependent on the integrity of phase-locked neural activity in the auditory brainstem (Worden & Marsh, 1968). It has been established as a valid and reliable means to assess the integrity of the neural transmission of speech stimuli at the brainstem.

Speech evoked ABR holds its importance in diagnosis of various pathologies. Speech evoked ABR has been evidenced to diagnose children with Learning disability (Banai et al., 2005; Cunningham, Nicol, Zecker, Bradlow & Kraus, 2001; Hayes, 2003; King, Warrier, Hayes & Kraus, 2002; Russo, Nicol, Zecker, Hayes & Kraus, 2005; Wible, Nicol & Kraus, ,2004; Wible, Nicol & Kraus, 2005), individuals with sensorineural hearing loss (Pyler & Ananthanarayan, 2001), children with poor readers skills (Hornickel, Skoe, Nicol, Zecker & Kraus, 2009), children with autistic spectrum disorder (Russo, Nicol, Trommer, Zecker & Kraus, 2009), aging (Vander, Kathy, Burns & Kristen, 2011) and speech-in-noise perception problems in older adults (Anderson, Parbery- Clark, Yi & Kraus, 2011).

Need for the study

1) Speech is complex acoustic token that undergo rapid spectral and amplitude modulations over time, and is what we hear in everyday situation. It is reasonable to hypothesize that a diminished ability to track these modulations must affect speech perception. The click-evoked ABR, however, is a gross measure of time-locked neural activity in response to stimulus onset. In contrast, the frequency-following response (FFR) is a steady state AEP that is sensitive to sustained features within a stimulus and is dependent on the integrity of phase-locked neural activity in the auditory brainstem (Worden & Marsh, 1968). Thus there is a need to study speech evoked ABR.

2) The processing of speech sounds is potentially more “meaningful” than the processing of any non-speech sound. Speech-evoked ABR recordings may have diagnostic and clinical management implications to help screen or identify patients with abnormal speech processing or perhaps those with auditory processing disorders (Khaladkar, Kartik, & Vanaja, 2005). Thus, there is a need to study processing of speech sound in normal aging adults.

3) Several authors have reported that brainstem responses faithfully replicates the signals as presented at the brainstem level. Brainstem responses elicited by speech are reported to evidence even the subtle changes in the signals (Tremblay, Billings, Friesen & Souza, 2003). Compared to cortical potentials, the scalp recorded FFR is highly consistent, smaller in amplitude, less susceptible to adaptation with repetition, and demonstrates earlier maturation, is capable of robustly representing the temporal structure in speech with a resolution on the order of 1ms (Chandrashekhran & Kraus, 2010). Thus there is a need to study temporal processing at the brainstem level.

4) By increasing the repetition rate of the stimuli, the auditory temporal processing can be checked, the auditory temporal processing is one of the major requisite for the normal auditory processing. By utilizing speech stimulus for checking the temporal processing will give additional information about temporal coding of speech at the brainstem. Impaired speech understanding in aging adversely affects the ability to process temporal cues (Frisina & Frisina, 1997). Thus there is a need to study temporal processing in older adults.

5) There are several evidences that the age-related deficits start relatively early in life. Deficits of temporal processing have been found in a group of 40–55 year-old individuals (Grose, Hall & Buss, 2006), reduced gap detection ability in middle-aged women (Helfer & Vargo, 2006), reduced DPOAE amplitudes in normal-hearing middle-aged adults (Dorn, Piskorski, Keefe, Neely & Gorga, 1998), subtle differences in auditory perception between younger and older adults in auditory event-related potential (Alain, McDonald, Ostroff & Schneider, 2004; Geal-Dor, Goldstein, Kamenir & Babkoff, 2006) processing of inter aural phase differences both in behavioral and physiological tasks (Ross, Fujioka, Tremblay & Picton, 2007) demonstrating that age-dependent subtle auditory changes may begin in older adults . Thus there is a need to study the temporal processing of speech in older adults.

Aims of the study

1) To investigate the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on speech evoked and click evoked ABR in normal hearing younger adults and older adults.

2) To check whether the stimulus rate affects the encoding of the onset of the response or the sustained portion of the response in older adults.

Chapter -2

Review of literature

Perception of acoustic signals depends on accurate neural encoding of temporal events of auditory signals. The auditory brainstem reflects processing of temporal events that are diagnostically significant in the assessment of hearing loss and neurological function (Hall, 1992). The ABR is a far field recording of stimulus- locked synchronous neural events. The human ABR to complex sounds reveals distinct aspects of auditory processing in normal hearing individuals and clinical populations that may reflect differences in the encoding and processing of temporal cues. By manipulating the stimulus presentation rate, helping to reveal minute differences in how temporal cues are processed in various populations.

2.1 Hearing thresholds in older adults

A decline in hearing sensitivity is considered a likely consequence of age (Gates & Cooper, 1991; Hull, 1989). However, some initial signs of auditory aging start long before senescence. Ross, Fujioka, Tramblay and Picton (2007) reported that age-related change in physiological thresholds shows that phase synchrony deteriorates with increasing age and, most importantly, this process commences before midlife. A recent behavioral study showed that binaural advantage for speech understanding in noise was already reduced in middle-aged adults, who, in contrast, performed like young listeners in quiet (Kim, Frisina, Mapes, Hickman & Frisina, 2006) thus providing the physiological evidence for early onset of aging in central auditory function of binaural hearing.

Numerous studies have reported deterioration of hearing levels at 45–50 years of age and then a notable acceleration above 70 years (Gates & Cooper, 1991; Robinson & Sutton, 1978; Ross et al., 2007; Shuknecht, 1955, 1964, 1974). Hutchinson, Alessio and Baiduc

(2010) reported that hearing sensitivity is at its peak in the teens and 20’s, regardless of fitness level and the pure tone thresholds decline over time.

Hearing sensitivity declines gradually and progressively with aging in both males and females, however, it progresses faster in men compared to women. Gordon- Salant et al. (1995) conducted a study of the normal progression of hearing thresholds across the adult life span (ages 20 to 90+). The authors reported that the longitudinal hearing threshold changes in the men and women across the adult age span, for five audiometric frequencies. The data indicate that the decline in hearing sensitivity accelerates above age 20 to 30 in men, and above age 50 in women. At most ages and frequencies, the amount of longitudinal change in hearing level over 10 years is more than twice as fast for the men than the women as shown in figure 2.1.

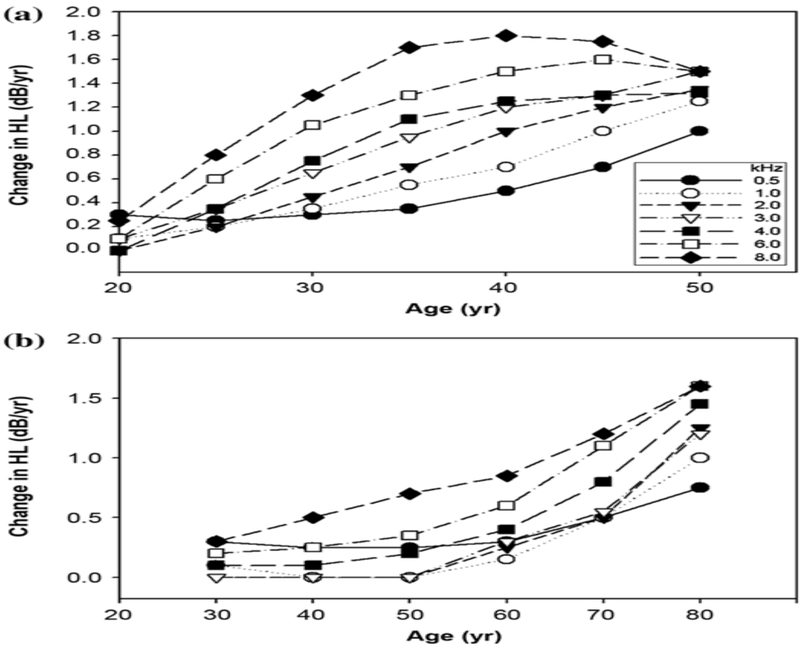

Figure 2.1.Average 10-year longitudinal changes in pure-tone hearing level (HL) thresholds across frequency for **(**a) men and (b**)** women.

Klein et al. (1998) collected a cross-sectional data of average hearing thresholds in large populations of unscreened elderly adults and reported that hearing thresholds of men are typically poorer than those of women in the high frequencies, with men exhibiting a sharply sloping hearing loss in the moderately severe range in the high frequencies, and the women exhibiting a more gradual sloping hearing loss in the moderate range in the high frequencies as shown in figure 2.2.

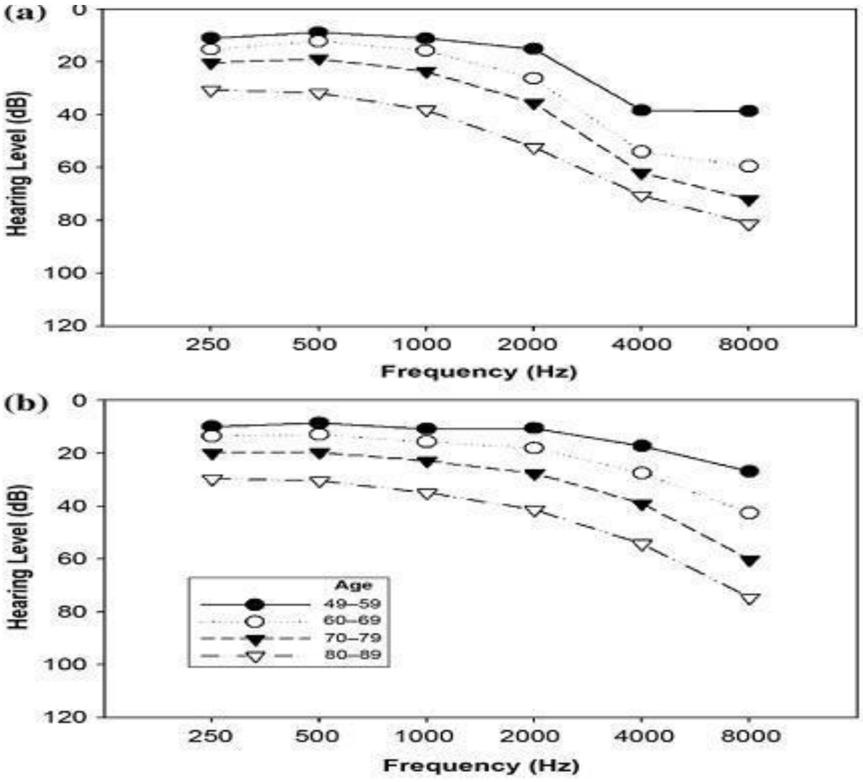

Figure 2.2. Mean pure-tone air conduction thresholds for (a) men and (b) women in four age groups.

2.2 Speech Identification Scores in older adults

Perhaps the most important consequence of the decline in hearing sensitivity with aging is difficulty understanding speech. Gelfand, Piper and Silman (1985) obtained consonant recognition scores in quiet using the Nonsense Syllable Test (NST) from62 normal hearing subjects 20 to 65 years of age at their most comfortable listening levels (MCLs) and at 8 dB above and below MCL. The authors reported that the consonant recognition decreases with normal aging, particularly below MCL and that the normal hearing older individuals listening in quiet have decreased consonant recognition ability, but that their confusions are similar to those of younger persons

Bess, Konkle and Beasley (1977) assessed intelligibility of time-altered speech in relation to chronological aging by time compressing the Auditory Test Number 6 (NU-6), measure of speech discrimination and presented to four age groups ranging from 54 to 84 years of age at sensation levels of 24, 32, and 40 dB. The authors reported that intelligibility decreased as a function of increasing time compression and age and decreasing sensation level. Changes in speech intelligibility associated with the aging process appear to be closely allied to changes in the temporal resolving power of the central auditory processing system.

Dubno, Horwitz and Ahlstrom (1997) reported that speech-recognition performance of elderly males declined significantly with age after adjusting for average hearing thresholds, but no significant changes were found in speech recognition with age for females in the same age range (55–84 years). In contrast, Wiley, Cruickshanks, Nondahl, Tweed, Klein and Klein (1998) reported that from a large cohort of adults (48–92 years) , a significant age effects in word recognition scores in competing messages for both men and women, but performance is consistently poorer in men than in women at all age groups and hearing loss categories.

2.3 Oto acoustic emission findings in older adults

DPOAE amplitudes ,checked in a population from 5 to 79.9 years, are smaller in normal-hearing middle-aged adults than in normal-hearing younger adults (Dorn, Piskorski, Keefe, Neely & Gorga, 1998), suggesting that subtle peripheral auditory changes may begin in this age range. Prieve and Falter (1995) reported lower prevalence of SOAES in middle aged normal hearing individuals of 40 to 61 years compared to young adults of 19 to 29 years. The important conclusion drawn by Lonsbury- Martin, Cutler and Martin (1991) and compared with a Bonfils (1989) is that the ability of a human ear to generate SOAEs depends systematically on age, with older ears being less capable of generating and/ or emitting this type of emission than younger ears.

Stoll, Hustert and Nieschalk (1998) investigated DPOAEs in middle aged normal hearing individuals and reported that one peak region was associated with lower frequency primaries around 1.5kHz and another region of maximum response was found for higher frequency primaries at approximately 5.5 to 6.2kHz. The authors reported that between these two energy peaks, there was a mid frequency region known to consist of smaller- level DPOAEs. The authors also reported multi- sourced DPOAE generators, the presence of a third, residual 2f1-f2 DPOAE component around 75- 80 dB below the stimulus levels which may reflect the true passive distortion response of the cochlea and found two clearly separated components of the 2f1-f2 DPOAE I-Os, the first component, in response to primary intensities of 60 dBSPL and below, showed a plateau (saturating) behaviour. When primaries exceeded 60 dBSPL, I-O functions became more linear.

2.4 Auditory brainstem responses in older adults individuals

Rosenhamer, Linstrom and Lundborg (1980) recorded brain stem electric responses (BSER) to clicks at 80, 60 and 40 dB SL (rate 22.5/sec) from 62 normally hearing subjects grouped: young females (mean age 26.8 years), old females (56.1 years), young males (29.6 years), and old males (59.3 years). Wave replicability was seen to deteriorate with age. Concerning peak latencies, young females exhibited significantly shorter latencies (of the order of 0.2 msec); differences between the other three groups were not significant and in old subject, III–V interval exhibited a significant increase with reduction of click intensity from 80 to 60 dB SL of the order of 0.1 msec.

It has been reported that the timing of auditory nerve conduction increases with age. Patterson, Michalewski, Thompson, Bowmanm and Litzelman (1981) conducted brainstem auditory evoked response (BAER) in older (60 to 79 yrs), middle-aged (40 to 59 years), and young (20 to 39 yrs) individuals. The results suggest that age affects neural propagation at the level of the olivary complex (Wave III) and that BAER latencies are also influenced by the sex of the individual. Some studies have reported the latencies of waves I, III, or V to increase with age (Allison, Wood & Goff , 1983; Hyde, 1985; Patterson et al., 1981; Rosenhamer et al., 1980; Rowe, 1978; Schwartz & Berry, 1985). Trune, Mitchell and Phillips (1987) studied the importance of age (14-71 years) in ABR and reported that age was significantly correlated only with the latency of wave III.

It is evident in literature that variable repetition rate has a significant effect on ABR waves. Don, Allen and Starr (1977) have reported a wave V latency shift by 0.9 msec when click repetition rate was increased from 10/sc to 100/sec in normal hearing adults of age range 18- 37 years. Mamatha and Barman (2008) recorded ABR for click across ages 30-40, 40-50, 50-65 years for normals and SNHL at 11.1/s, 30.1/s,65.1/s and 90.1/s and found that the latencies of wave I, III and V increased with the increase in repetition rate within the subjects and across age groups for the same repetition rate.

Jewett, Romano and Williston (1970) have described the effect of stimulus rate on ABR in normal hearing adults. They found that stimulus repetition rate upto approximately 20/sec have little effect on ABR, but above this level, ABR latency generally increase and amplitude decreases as rate increases. These changes are different for each wave component. Wave V amplitude appears to show less decrement with increasing rate (8-10/sec - 80-90/sec) than earlier components and also wave VI.

2.5 Temporal processing deficits in older adults individuals

It has been generally established that, with aging, individuals experience a decreased ability to recognize rapid speech, even in the presence of normal hearing. The appropriate use of speech cues relies on auditory temporal resolution that has been shown to decline with age (Pichora-Fuller & Souza, 2003; Schneider, Daneman & Pichora- Fuller, 2002; Schneider & Pichora-Fuller, 2001). Babkoff, Ben- Artzi and Fostick (2011) examined the age-related decline in auditory temporal resolution and in working memory in 82 participants, aged 21-82 for the dichotic temporal order judgment task and the backward digit span task. The findings indicate that age-related decline occurs in auditory temporal resolution and in working memory.

Deficits of temporal processing were already found in a group of 40–55 year-old individuals. Musiek et al. (2005) carried out Gaps-In-Noise (GIN) test, 0 to 3 silent intervals ranging from 2 to 20 msec embedded in 6-sec segments of white noise for assessment of temporal resolution in patients of age 20 to 65 years with confirmed neurological involvement of the central auditory nervous system and found a statistically significant increase in gap detection thresholds compared to the control group. Data from many of the studies suggest that certain auditory abilities begin to decline in middle age. Middle-aged subjects have been shown to perform more poorly than younger listeners (but better than older individuals) on duration discrimination (Abel, Krever & Alberti , 1990).

Helfer and Vargo (2006) used Gaps-In-Noise (GIN) test (Musiek et al., 2005) to assess temporal resolution ability and suggested that some middle-aged women with little or no pure-tone hearing loss experience listening difficulty in complex environments and also suggested a strong relationship between temporal processing and speech understanding in certain competing speech situations. The changes in auditory perception in middle age may at least in part be due to factors beyond the cochlea.

Grose, Hall and Buss (2006) measured two aspects of temporal hearing (gap duration detection and gap duration leading to perception of a stop consonant within a word [e.g., say vs. stay]) in younger and middle-aged (40–55 years) adults with normal hearing. Results of both of these experiments suggested age-related temporal processing change demonstrated in middle age and that they may lead to subtle problems processing speech stimuli.

Abel et al. (1990) measured duration discrimination in several populations, including a group of young normal-hearing listeners (20–35 years) and a group of normal-hearing middle-aged listeners (40–60 years). They found that these two groups differed in their ability to discriminate the duration of brief (20 ms) stimuli. Temporal processing deficits are evident in the pre-senescent (middle-aged) auditory system for listening tasks that involve brief stimuli, across-frequency channel processing, and/or significant processing loads.

Grose et al. (2006) conducted a study wherein they took total of 18 young and 23 middle-aged listeners (40-55 yrs) with normal hearing in the Gap Duartion Discrimination experiments. The results indicated that middle-aged listeners performed more poorly than the young listeners in general, and that this deficit was sometimes, but not always, exacerbated by increases in task complexity. A categorical perception task that measured the gap duration associated with a perceptual boundary indicated that the categorical boundary was associated with shorter gaps in the young listeners compared to middle age. The results of these experiments indicate that temporal processing deficits can be observed relatively early in the aging process, and are evident in middle age.

In terms of electrophysiological evidence for pre-senescent deficits in temporal processing, some differences between young and middle-aged listeners are apparent in the N1-P2 response elicited as a function of stimulus duration (Ostroff, McDonald, Schneider & Alain, 2003). Also using click stimuli, Babkoff et al. (2002) confirmed that the sensitivity for ITD but not for IID decreases with increasing age. Those findings seem to be consistent with the general notion that sensory processing of temporal information declines with age (Strouse, Ashmead, Ohde & Grantham, 1998; Schneider & Hamstra, 1999).

2.6 Speech evoked ABR

Speech evoked ABR waveforms to a syllable /da/ comprises of onset response and sustained peaks which is also known as frequency following response (FFR). The onset response is a transient event that signals the beginning of the sound. In the case of consonants, the transient onset response marks the beginning portion of the consonant characterized by unvoiced, broadband frication. The sustained FFR is synchronized to the periodicity of the sound, with each cycle faithfully representing the temporal structure of the sound. Thus, the sustained FFR reflects neural phase locking with an upper limit of about 1000 Hz (Chandrasekharan & Kraus, 2010).

The response to the onset of the speech stimulus /da/ includes a positive peak (wave V). Likely analogous to wave V elicited by click stimuli, followed immediately by a negative trough (wave A). In most subjects, positive peaks corresponding to click evoked ABR waves I and III are also visible. Peaks of FFR occurs at approximately 15ms, 24ms, and 33ms in stimulus corresponding to wave D (22)ms, E(31)ms, F(40)ms in response. These FFR peaks involve the encoding or periodicity and are prominent enough to provide reliable latency information. There is also an offset response to the stimulus which is known as "O". The defining feature of the sustained portion of the response is its periodicity, which follows the frequency information contained in the stimulus (Marsh, Brown, & Smith, 1974; Smith, Marsh & Brown, 1975). The figure 2.3 shows a stimulus waveform and a representative response waveform:

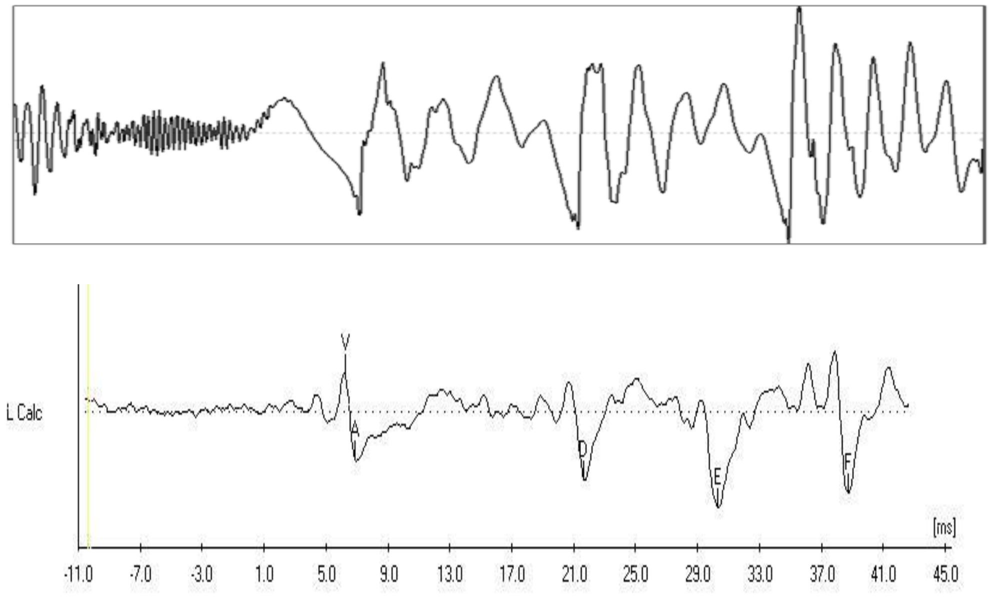

Figure 2.3. The top panel shows the stimulus waveform of /da/ and the bottom panel shows a representative response waveform.

2.7 Applications of Speech evoked ABR

2.7.1 Speech evoked ABR in learning impaired children

There has been significant research in brainstem encoding of speech syllables in learning impaired children. Both the transient responses and the sustained responses have been studied in learning impaired children. A consistent finding is that about one third of Learning problem children exhibit a unique pattern of auditory neural activity that distinguish them from the larger learning problem population (Banai, Nicol, Zecker & Kraus, 2005; Cunningham, Nicol, Zecker, Bradlow & Kraus, 2001; Hayes, 2003; King, Warrier, Hayes & Kraus, 2002; Russo, Nicol, Zecker, Hayes & Kraus, 2005; Wible, Nicol & Kraus, 2004; Wible, Nicol & Kraus, 2005). These children exhibit delayed peak latency or shallower slope measures of the VA onset complex and of waves C and O, indicating poor synchrony to transient events.

There are reports which suggest that deficits in cortical processing are associated with the delay in auditory brainstem responses of learning impaired children. King et al. (2002) recorded auditory brainstem responses in normal children and children diagnosed with a learning problem to a click stimulus and the speech stimulus /da/. They observed no latency differences for click stimuli, whereas for the syllable /da/ there was a significant latency difference between normal and learning impaired children. Deficits in cortical processing of signals in noise were seen for the learning disabled children with delayed brainstem responses to /da/, but not for learning impaired children with normal brainstem response measures. In addition, children with delayed onset responses to a speech stimulus also have delays in FFR. The effect of these brainstem neural timing deficits on speech perception in quiet is not evident. However, in the presence of noise, the deficits seen at the level of brainstem appear to have a deleterious effect on cortical responses to the same stimulus.

Cunnigham et al. (2001), studied the auditory brain-stem responses, frequency-following responses and in a group of 9 Learning Problem children and compared to responses in 9 normal children, reported abnormalities in the fundamental sensory representation of sound at brain-stem level when speech sounds were presented in noise, but not in quiet. The neurophysiologic responses from these LP children displayed a different spectral pattern and lacked precision in the neural representation of key stimulus features and the preconscious biological processes underlying perception deficits.

It has been reported that the wave V-A of speech ABR is shallower in LD children. Wible et al. (2004) investigated how the human auditory brainstem represents elements of speech sounds differently in eleven children with language based learning problem, especially under stress of rapid stimulation compared to nine typically developing children. In response to the onset of the speech sound /da/, wave V-A of the auditory brainstem response (ABR) had a significantly shallower shape in learning impaired children, suggesting longer duration and/or smaller amplitude. They observed that poor representation of crucial components of speech sounds could contribute to difficulties with high level language processes.

Speech-ABR can be used to identify a large sub-population of LDs, those with abnormal auditory physiological function. It has been reported that abnormal brainstem timing in learning disabilities obtained through speech evoked ABR is related to higher incidence of reduced cortical sensitivity to acoustic change and to deficient literacy skills. Banai et al. (2005) obtained speech evoked ABR for syllable /da/ and reported that LD individuals with abnormal brainstem timing were more likely to show reduced processing of acoustic change at the cortical level compared with both normal-learning individuals and LD individuals with normal brainstem timing. The authors reported that this group was also characterized by a more severe form of learning disability manifested by poorer reading, listening comprehension, and general cognitive ability suggesting that abnormal brainstem timing may serve as a reliable marker of a subgroup of individuals with learning disabilities.

2.7.2 Speech evoked ABR in individuals with Sensorineural hearing loss (SNHL)

Both the transient response and the FFR are affected in SNHL. It has been reported in literature that the coding of the second formant transition is affected in SNHL. Pyler and Ananthanarayan (2001) reported that the FFR did encode the second formant transition in normal hearing listeners. However, in SNHL, degradation in the encoding of the second formant transition was also associated with the reduction in the identification performance of stop consonants.

There are also reports that the transient portion of the speech evoked ABR is affected in SNHL. Khaladkar, Kartik and Vanaja (2005) obtained Auditory brainstem responses (ABRs) on 20 ears with mild to moderate SNHL. Two stimuli were used to evoke the ABR; a standard acoustic click and the burst portion of the syllable /t/. The authors reported that ABR wave V latency for the click stimulus was within normal limits, whereas speech burst ABR showed deviant results in SNHL, suggesting that speech ABR offers an opportunity to isolate normal speech processing from abnormal speech processing. Further, as the degree of SNHL increases, the coding of the speech parameters are more effected at the brainstem.

Sumesh and Barman (2010) explored the relationship between the cochlear hearing loss and the brainstem encoding of the speech sound. They noticed that the amplitude and latency parameters obtained from the control group and the cochlear hearing loss group was significantly different for some parameters (latency and amplitude). Further, they also noticed that the transient and FFR were more affected with the increase in severity of hearing loss. The authors attributed this finding to difficulty in coding temporal fine structure by cochlear hearing loss group.

2.7.3 Speech evoked ABR in Reading disorders

Impaired perception of consonants by poor readers is reflected in poor subcortical encoding of speech timing and harmonics. Hornickel, Skoe, Nicol, Zecker and Kraus (2009) investigated whether the subcortical differentiation of stop consonants is related to reading ability and speech- in- noise performance. Authors found that across a group of children with a wide range of reading ability, the subcortical differentiation of 3 speech stimuli (/ba/, /da/, /ga/) was found to be correlated with phonological awareness, reading and speech in noise perception. Based on their results they suggested that the neural processes underlying phonological and speech in noise perception depend on reciprocal interaction between cognitive and perceptual processes.

Banai et al. (2009) observed that speech evoked ABR latencies were prolonged for the poor readers compare to good readers. Also, the encoding of the pitch and the harmonics was affected in the poor readers compare to good readers. The authors suggested that the reading skills may depend on integrity of subcortical auditory mechanisms and are consistent with the idea that subcortical representation of acoustic features of speech may play a role in normal reading as well as in development of reading disorders.

Hornickel, Anderson, Skoe, Yi and Kraus (2011) assessed auditory brainstem representation of higher harmonics within a consonant vowel formant transition to identify relationships between speech fine structure and reading. Responses were analyzed in three ways: a single stimulus polarity, adding responses to inverted polarities (emphasizing low harmonics), and subtracting responses to inverted polarities (emphasizing high harmonics). They found that the poor readers had a reduced representation of higher speech harmonics for subtracted polarities and a single polarity. No group differences were found for the fundamental frequency. The authors attributed these findings to subcortical encoding deficits in poor readers for speech fine structure.

2.7.4 Speech evoked ABR in Autism

Russo et al. (2008) investigated the subcortical representation of prosodic speech in children with autistic spectrum disorder. They recorded brainstem responses to speech syllables /ya/ with descending and ascending pitch contours and a click stimulus. They observed that some children on the autism spectrum show deficient pitch tracking compared with typically developing normal children. There was no significant difference in terms of latency or the amplitude of ABR evoked by click stimulus. Thus, the authors concluded that speech evoked ABR may have clinical implications for diagnostic and remediation strategies in a subset of children with autistic spectrum disorder.

Russo, Nicol, Trommer, Zecker, and Kraus (2009) measured brainstem responses to syllable /da/ in quiet and in background noise in children with autistic spectrum disorder who had normal intelligence and hearing. Children with autistic spectrum disorder exhibit deficits in both the transient responses (i.e. wave V and wave A) and sustained responses (frequency following responses) despite normal click-evoked brainstem responses. Children with autistic spectrum disorder also show reduced magnitude and fidelity of speech- evoked responses and inordinate degradation of responses by background noise in comparison to typically developing controls. The authors suggested that the speech-evoked brainstem response may serve as a clinical tool to assess auditory processing in children with autistic spectrum disorder.

2.7.5 Speech evoked ABR – Developmental changes

It has been reported that with developmental changes occur in form of experience-dependent developmental plasticity in the mammalian auditory brainstem in the human system. Johnson, Nicol, Zecker and Kraus (2008) recorded brainstem responses evoked by both click and speech syllables in children between the ages of 3 and 12 years. Whereas all children exhibited identical neural activity to a click, 3- to 4-year-old children displayed delayed and less synchronous onset and sustained neural response activity when elicited by speech compared with 5- to 12-year-olds suggesting that the human auditory system exhibits developmental plasticity, in both frequency and time domains, for sounds that are composed of acoustic elements relevant to speech.

Ranjan (2011) recorded click ABR and speech evoked ABR for /da/ in 57 children in 5 groups in the age range of 5 to 9.11 years (5 to 5.11, 6 to 6.11, 7 to 7.11, 8 to 8.11 and 9 to 9.11 years). The authors reported that with click ABR, there was no change in wave V latency and amplitude for each group and across groups. And also for speech ABR, no significant change was seen for the transient and the sustained responses. The authors concluded that neural processing of temporal aspects of speech stabilizes before 5 years of age.

2.7.6 Speech evoked ABR – Older individuals

Vander, Kathy, Burns and Kristen (2011) recorded click and speech-evoked ABRs(S-ABR) using a synthetic 40-msec /da/ stimulus in normal hearing younger adults and older adults. Results suggested age-related differences in neural processing of speech at the brain stem level, with significant delays in the timing of the offset portion of the S-ABR in older listeners compared with their younger counterparts, also significant reductions in amplitude of the S-ABR at the onset. These results are consistent with a reduction in neural synchrony in older adults to transient components of both speech and nonspeech sounds. However, sustained components of the S-ABR, which follow the harmonic components of the syllable, showed group differences but were not significant after adjusting for peripheral hearing loss. Several lines of evidence suggest that central deficits of auditory temporal processing contribute to the deterioration of speech perception in older individuals. In particular, the ability of neurons in the central auditory system to accurately encode important temporal features of speech may be limited by impaired neural synchrony, slowed neural conduction time, reduced phase-locking abilities, or other mechanisms in older adults.

Anderson, Parbery- Clark, Yi and Kraus (2011) investigated a neural basis of speech-in-noise perception in older adults (28 adults, age 60–73 yr), speech-evoked auditory brainstem responses were recorded in quiet and in background noise. The authors reported that in the quiet condition, the poorer speech-in-noise (SIN) group had reduced neural representation of the fundamental frequency and in the noise condition; greater disruption was seen, reflecting reduction in neural synchrony. Thus, the older adults with poorer SIN perception demonstrate impairments in the subcortical representation of speech.

2.7.7 Speech evoked ABR – Musicians

Work on music evoked ABR has included a bowed cello note (Musacchia, Sams, Skoe & Kraus, 2007; Musacchia, Strait & Kraus, 2008), a five- note melody (Skoe & Kraus, 2009), as well as consonant and dissonant two- tone intervals synthesized from an electric piano (Lee, Skoe, Kraus & Ashley, 2009). And tone complexes (Greenberg, Marsh, Brown & Smith, 1987; Bidelman & Krishnan, 2009).

In literature, studies have shown that potentials evoked from primarily brainstem structures are enhanced in musicians, compared to non-musicians. Specifically, musicians have more robust representations of pitch periodicity and faster neural timing to sound onset when listening to sounds or both listening to and viewing a speaker. Musacchia et al. (2008) recorded speech ABR responses to /da/ stimulus and cortical evoked responses in musician and non-musician subjects and reported that brainstem response periodicity was related to early cortical response timing across all subjects, and this relationship was stronger in musicians. The authors concluded that the neural representations of pitch, timing and timbre cues and cortical response timing are shaped in a coordinated manner, and indicate corticofugal modulation of subcortical afferent circuitry.

Several recent studies have found that the quality of subcortical speech sound encoding is significantly greater in musically trained individuals (e.g., Musacchia et al., 2007; Wong, Skoe, Russo, Dees & Kraus, 2007; Lee et al., 2009; Parbery-Clark, Skoe & Kraus, 2009; Strait, Skoe, Kraus & Ashley, 2009). It has been reported that music provides the first biological evidence for musicians perceptual advantage for speech-in-noise as evidenced by speech evoked ABR. Parbery-Clark et al. (2009) compared subcortical neurophysiological responses to speech in quiet and noise in a group of highly trained musicians and nonmusician controls. The authors reported that the musicians were found to have a more robust subcortical representation of the acoustic stimulus in the presence of noise and they demonstrated faster neural timing, enhanced representation of speech harmonics, and less degraded response morphology in noise.

Wong et al. (2007) examined the FFR in musically trained and untrained individuals and the native English speakers unfamiliar with Mandarin listened passively to the Mandarin syllable /mi/ (pronounced “me”) with three different lexical tones. The salient finding was that the quality of F0 tracking was superior in musically trained individuals.

2.7.8 Speech evoked ABR – Training related changes

It is noteworthy that learning problem children with abnormal brainstem timing of peaks A and C are most likely to show both physiological and behavioural improvements after auditory training with commercially available software (Hayes 2003; King et al., 2002; Russo et al., 2005). Thus, the brainstem response to speech can serve to inform recommendations of treatment strategies by providing an objective indication that a child is likely to benefit from an auditory training program.

In brainstem response itself, training- related changes have been reported in the FFR but not the onset response (Russo et al., 2005). After training, FFRs to speech presented in background noise became more robust and better synchronized. The improvements seen with training can be viewed as reflecting more accurate neural encoding of filter information (neural activity relating to F1) because the source information (neural activity relating to F0) remained stable. It is therefore possible that auditory training has the effect of making aggregate neural activity less susceptible to detrimental effects of background noise.

Learning problem children who completed auditory training also showed improved cortical responses to speech syllables in noise (Hayes , 2003; King et al., 2002; Russo et al., 2005; Warrier, Johnson, Hayes, Nicol & Kraus, 2004). These Learning problem children also improved on a behavioural speech perception task (King et al., 2002) and tests of phoneme decoding and literacy (Hayes, 2003).

2.7.9 Temporal processing studies using speech evoked ABR

Krizman, Skoe and Kraus (2010) studied complexity of the temporal processing of speech using speech ABR through different stimulation rate in normal hearing adults. The results suggested that the click response was invariant with changes in stimulus rate, timing of the onset response to /da/ varied systematically, increasing in peak latency as presentation rate increased. Contrasts between the click and speech response likely reflect acoustic differences. The FFR was also rate dependent, with response magnitude of the higher frequencies (>400Hz), but not the frequencies corresponding to fundamental frequency, diminishing with increasing rate. Rate affected the FFR with higher frequencies becoming increasingly rate sensitive while lower frequencies remained rate resistant. The selective impact of rate on high frequency components of the FFR indicated the involvement of distinct underlying neural mechanism for high versus low frequency components of the response.

There are a lot of studies which support the existence of separate neural mechanisms for the onset response and FFR (Akhoun et al., 2008; Chandrashekaran & Kraus, 2010; Hoormann, Falkenstein, Hohnsbein & Blanke, 1992; Hornickel, Skoe & Kraus, 2009). Akhoun et al. (2008) reported that as stimulus intensity decreased the onset response and FFR both increased in latency. However the FFR increased at a greater rate than the onset response. Also, Basu, Krishnan and Fox (2010) reported that with an increase in repetition rate there was a decrease in FFR amplitude in normal developing children. The reduction in the amplitude of FFR can be as FFR reflects sustained phase- locking among a population of the neural elements within the rostral brainstem (Worden & Marsh, 1968; Marsh, Brown & Smith, 1974; Smith, Marsh & Brown, 1975) and the amplitude of the FFR is directly proportional to the number of neural elements exhibiting synchronized neural phase- locking. Gonclaves, Wertzner, Samelli and Matas (2011) also reported decrease in the amplitude of the speech evoked ABR with increase in the repetition rate. The author highlighted that these responses represent different building blocks of the message, which have different encoding demands.

By varying the presentation rate, the speech ABR then, manipulates the neurophysiological mechanisms underlying the sub-cortical encoding of timing, thereby elucidating what happens to the population- wide neural response when the stimulus is manipulated along this temporal dimension. Mehta & Singh (2012) compared typically developing children and children with LD on speech ABR using /da/ stimulus for three repetition rates 6.9/s, 10.9/s and 15.4/s. The authors reported that with the increase in the repetition rate, the coding of the onset is affected in both typically developing children and children with LD i.e. the stimulus rate did not generalize to the entire response but were specific to the timing of the onset portion in both the groups and there exists atleast two different categories in LD, one in whom timing information is retained and the other in whom timing information is severely impaired.

Ranjan (2011) obtained click ABR at 9.1/s, 19.1/s, 40.1/s and speech ABR to /da/ at 6.9/s, 10.9/s, 15.4/s in the typically developing children in the age range of 5 to 9.11 years (5 to 5.11, 6 to 6.11, 7 to 7.11, 8 to 8.11 and 9 to 9.11 years). The authors reported that rate did not have any effect on encoding of click but had a significant effect on processing of speech ABR and FFR and the transient components are more susceptible to change with rate but sustained responses may not show significant changes. This could be due to the fact that higher repetition rate causes neural fatigue and neural dysfunction due to depletion of neuro-transmitter at the hair cell- nerve junction more for the speech ABR components compared to the click evoked ABR.

In summary, a substantial body of work has established that temporal processing declines with advanced age, and independently of hearing loss, but there has been little focus on the emergence of these temporal deficits in the presenescent, or middle-aged, auditory system. The evidence to date suggests that such deficits may be identified in listening tasks that involve brief stimuli, particularly those that span disparate frequency channels. Furthermore, it is likely that any temporal processing deficits will be heightened when the listening tasks are complex.

Chapter-3

Method

The study was conducted with the aim of investigating the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on speech evoked and click evoked ABR in normal hearing young adults and older adults.

Participants

Participants of the present study were divided into two groups.

Group I: (Younger adults) - 17 Participants (30 ears) with normal hearing sensitivity in the age range of 18 to 30 years (Mean age= 21.8 years) participated in the study.

Group II: (Older adults)- 15 Participants (30 ears) with normal hearing sensitivity in the age range of 40 to 55 years (Mean age= 47.3 years) participated in the study. The mean and the standard deviation of the thresholds at the octave frequencies for the young and older adult group is given in figure 3.1

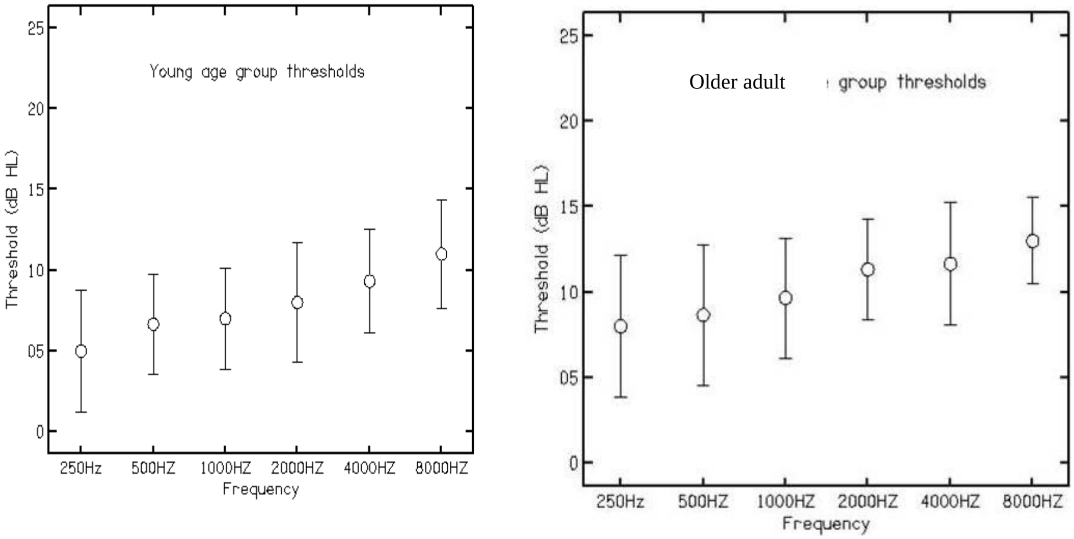

Figure 3.1. *Mean and the standard deviation of the thresholds at the octave frequencies for the young and older adult*

Participant selection criteria:

1. All the participants had normal hearing thresholds as evidenced by air conduction thresholds of less than or equal to 15 dB HL in the octave frequency range of 250 Hz to 8000 Hz and bone conduction thresholds of less than or equal to 15 dB HL in the octave frequency range of 250 Hz to 4000 Hz.
2. All the participants had normal middle ear functioning as evidenced by tympanometry and reflexometry results.
3. Participants did not have any history of otological or neurological problems.
4. The participants did not have diabetes (confirmed with medical reports).
5. The participants were not working in any industrial setup and did not have history of excessive noise exposure.
6. No known medical or surgically treatable ear related conditions.
7. No evidence of any retrocochlear pathology based on click evoked auditory brainstem responses.

Instrumentation

Following equipments were used for the study:

1) Pure Tone Audiometer

A two channel OB922 audiometer with TDH-39 head phone coupled to impedance matched TDH 39 earphones with MX-41/ AR ear cushions and a bone vibrator (Radio ear B-71) was used. It was used to obtain pure tone threshold at different frequencies for both air conduction and bone conduction.

2) Immittance meter

A calibrated automatic Immittance meter with a visual display (Grason - Stadler GSI-TS) was used to rule out middle ear abnormalities. Each ear of the participant was tested for the type of tympanogram and presence or absence of acoustic reflexes.

3) Evoked potential system

An evoked potential system (Biologic Navigator Pro EP) was used to record both click evoked and speech evoked ABR.

Test environment

All the audiological evaluation and recording were carried out in a sound treated room. The ambient noise was within the permissible limits as recommended by ANSI (S3.1; 1991).

Test Stimulus for speech ABR:

Figure 3.2 shows both the time and spectral domain of the stimulus used in the present study.

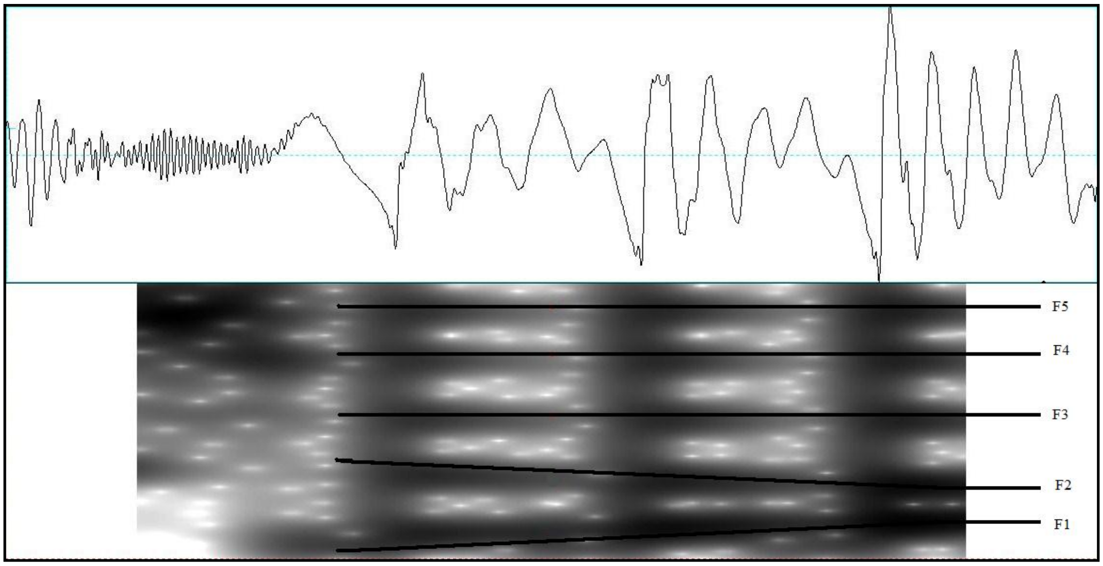

Figure 3.2 Spectral and temporal aspects of the Speech stimulus /da/ used in the present study. The top one represents the temporal details of the waveform whereas the bottom one depicts the spectral details.

The test stimulus which was used for speech evoked ABR in the present study was a synthesized /da/ syllable. The stimulus is available in evoked potential system with the BioMARK protocol. The /da/ stimulus is a 40 ms synthesized speech syllable produced using KLATT synthesizer (Klatt, 1980). This stimulus simultaneously contains broad spectral and fast temporal information characteristics of stop consonants, and spectrally rich formant transitions between the consonant and the steady-state vowel. Although the steady-state portion is not present, the stimulus is still perceived as being a consonant-vowel syllable. The fundamental frequency (F0) linearly rises from 103 to 125 Hz with voicing beginning at 5 ms and an onset noise burst during the first 10 msec. The first formant (F1) rises from 220 to 720 Hz, while the second formant (F2) decreases from 1700 to 1240 Hz over the duration of the stimulus. The third formant (F3) falls slightly from 2580 to 2500 Hz, while the fourth (F4) and fifth formants (F5) remain constant at 3600 and 4500 Hz, respectively.

Procedure

1)Pure tone audiometry

Behavioral air conduction and bone conduction thresholds were tracked using modified Hughson and Westlake procedure (Carhart & Jerger, 1959). Air conduction thresholds were obtained from 250Hz to 8 KHz and bone conduction thresholds were obtained from 250Hz to 4 KHz. Participants who had thresholds within 15 dB HL has further undergone immittance assessment in both the ears.

2) Tympanometry

Tympanometry was done to rule out pathology of middle ear using 226Hz probe tone. Immittance test was carried out by sweeping the pressure from +200 to -400 dapa. In reflexometry both ipsilateral and contralateral acoustic reflexes thresholds were measured for 500 Hz, 1000 Hz, 2000 Hz, and 4000Hz pure tone at the peak pressure.

3) Electrophysiological recording

Electrodes were placed on the sites with conduction paste and secured with skin tape. It was made sure that each electrode impedance was within <5 k Ω and inter electrode impedance was within <2 k Ω. Impedance for each electrode was also checked during testing, to make sure that patient movement did not cause any variation in the impedance. Participants were instructed to sit comfortably on a reclining chair and relax during the testing. They were instructed to close their eyes during the testing to avoid any artifacts. ABR were recorded twice for the reproducibility for both speech and non-speech stimuli.

Click ABR and Speech ABR was recorded using the following protocol (Table 3.1)-

Table 3.1

Parameters for recording click evoked ABR and speech evoked ABR

	Click evoked ABR	Speech evoked ABR
Stimulus, duration	Click, 100µs	CV syllable /da/, 40 ms
Level	80 dB SPL	80 dB SPL
Filter band	100 to 3000 Hz	100 to 3000 Hz
Rate	9.1/s, 19.1/s & 40.1/s	6.9/s, 10.9/s & 15.4/s
No of sweeps	2000	2000
Transducer	BioLogic Insert ear phone	BioLogic Insert ear phone
Polarity	Alternating	Alternating
Time window	12 ms	64 msec which included a prestimulus time of 10 msec (default setting in Biologic system)
Electrode montage	Non-inverting electrode: Forehead Inverting electrode: Test ear Mastoid Ground electrode: Non test ear mastoid.	Non-inverting electrode: Forehead Inverting electrode: Test ear Mastoid. Ground electrode: Non test ear mastoid.

Analysis of ABR recordings:

Analysis of click evoked ABR:

The representative waveforms for the click evoked ABR at 9.1 /s, 19.1 /s, and 40.1 /s are shown in figure 3.3. The following parameters were analyzed:

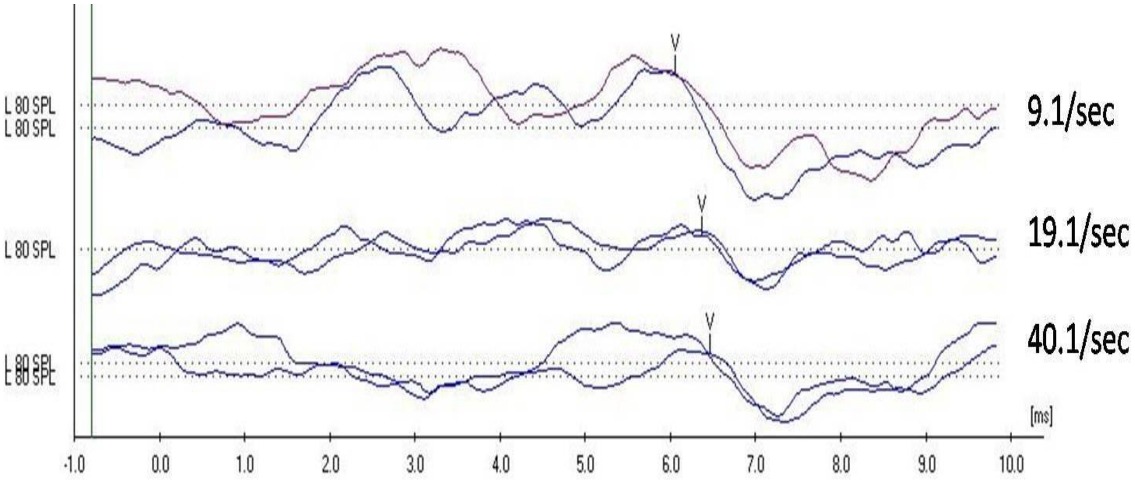

Figure 3.3 A representative waveform of click evoked ABR having replicable peaks at 9.1 /s, 19.1/s, and 40.1 /s respectively.

1) Peak latency of wave V: It is defined as the duration in msec between the onset of the stimulus and the highest amplitude of the wave V.

Analysis of Speech evoked ABR:

The electrophysiological brainstem responses to speech sound are a complex waveform. This includes onset peaks as well as sustained elements that comprise the FFR. The representative waveforms of speech evoked ABR at 6.9/s, 10.9/s, and 15.4/s are shown in figure 3.4. The following parameters were measured for all three repetition rates from each of speech ABR recordings:

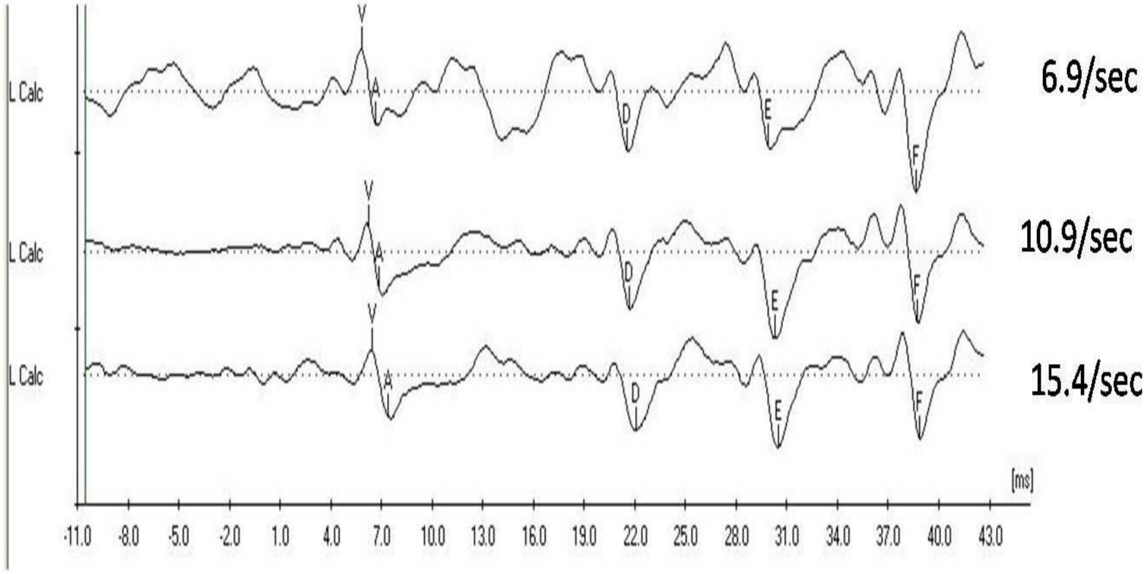

Figure 3.4 A representative waveform of speech evoked ABR having replicable peaks at 6.9/s, 10.9/s, and 15.4/s respectively.

a. *Onset responses:*

A composite was created from the latencies of the two onset peaks, V and A, which mark the onset of sound, and are comparable to the click-evoked peak V and Vn.

b. *Sustained responses:*

This composite was created from the latencies of peaks D, E, and F, which arise in response to the fundamental periodicity of the stimulus. To consider the presence of FFR, the fluctuations in the brainstem activity should repeat itself with a time period of approximately 10msec. The time period would correspond to the F0 (100Hz) of the stimulus frequency (Frequency= 1/ Time period). So the three major peaks which repeated itself at the time period of 10msec were considered as D, E, and F. The latency of D, E and F peaks were calculated.

c. *Pitch:*

The sustained FFR portion which occurs immediately after the onset response was subjected to FFT and it represents the FFT for the sustained portion. FFT was performed to obtain information regarding spectral characteristics of the FFR- frequency and amplitude of spectral peaks. Average spectral amplitude was calculated for a range encompassing the fundamental frequency (F0), 103–120 Hz. FFT was performed on all speech evoked potential using a custom made program run in MATLAB. The peak amplitude corresponding to F0 was also calculated using a custom made program file in the MATLAB platform. The frequency analysis was done from 11.4 to 40.6 msec. The sustained portion of the response (FFR) was passed through 103-120Hz band pass fourth order Butterworth filters in order to obtain the energy at F0. The Fourier analysis was performed on the filtered signal. A subject's responses were required to be above the noise floor in order to include in the analysis. This was performed by comparing the spectral magnitude of pre stimulus period to that of the response. If the quotient of the magnitude of F0 frequency component of FFR divided by the pre stimulus period was >1, the response was deemed to be above the noise floor.

d. *Harmonics:*

The Harmonics measure is a composite of the average spectral energy from two frequency bands: first formant (F1) 220 to 720 Hz, and high frequency (HF) 721–1154 Hz. F1 includes the harmonics of the stimulus that make up the most prominent frequencies of the first formant range in the analysis time of 11.4 to 40.6 msec. The HF range is composed of harmonics between the first and second formants (F1 and F2, respectively). For ease of reading, the high frequency band will be called as F2 throughout the dissertation. The sustained portion of the response (FFR) was passed through 200 to 720 band pass fourth order Butterworth filters in order to obtain the energy at F1. Because higher formants are above the phase locking limits of the brainstem, no higher frequency ranges were included.

The Figure 3.5 shows maximum amplitude in the F0 region i.e. around 103 to 125Hz. There is also some amount of energy in the F1 region i.e. from 220 to 720 Hz.

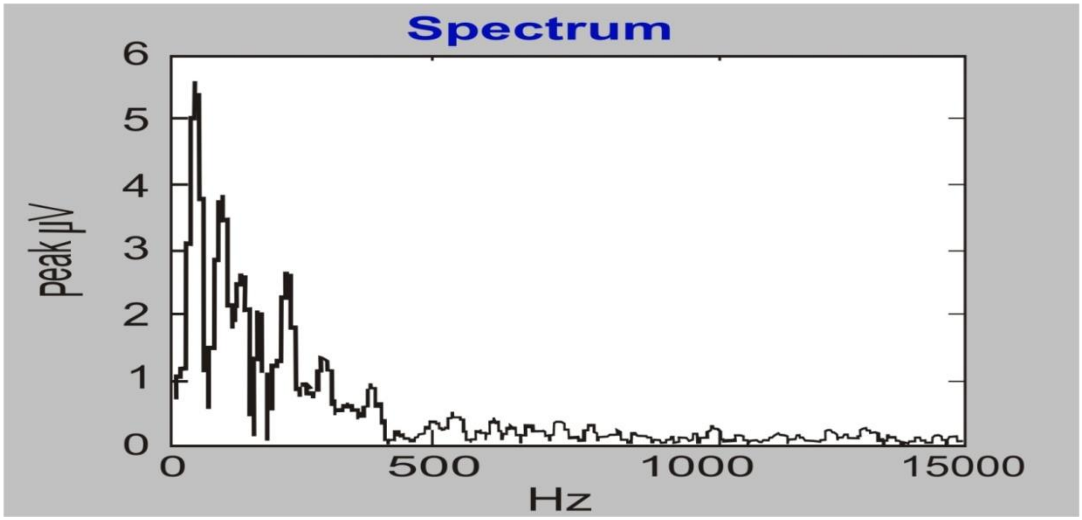

Figure 3.5 FFT representing the energies at fundamental and its harmonics.

Data Analysis:

Following analysis was done:

1) Latency of wave V of click evoked ABR for young group and older adults were analyzed.

2) Latency of onset response- wave V and wave A of speech evoked ABR for young group and older adults were analyzed

3) Latency of frequency following response- wave D, wave E and wave F of speech evoked ABR for young group and older adults were analyzed

4) Fast Fourier Transform to obtain the amplitude at F0, F1 and F2 for young groups and older adults.

Chapter 4

Results

The brainstem responses to click and speech stimulus were recorded at 80dBSPL across three repetition rates (6.9, 10.9 & 15.4/sec). The wave – V, A, D, E and F were identified and their latencies were noted. Fast Fourier Transform were done to find out the raw amplitude of F0, F1 and higher harmonics (F2) frequency components elicited by syllable /da/ using custom made program run on a MATLAB platform. The mean and the standard deviation (SD) for these parameters were calculated for all the groups at different repetition rates. The data obtained at different repetition rates were analyzed across the younger group and older adults group and also within the two groups.

Following statistical analysis were carried out to see the effect of repetition rate on click evoked ABR and speech evoked transient and sustained responses.

1) Mixed ANOVA was done to see the significant interaction across the two groups and the three repetition rates.
2) Pairwise comparison was done across the group to see the significant difference in data obtained across the repetition rates as the Mixed ANOVA showed interaction between waves and the repetition rates.
3) Repeated measure ANOVA was done within each group to see significant difference in data obtained across repetition rates.
4) Bonferroni post hoc test was done where Mixed ANOVA or Repeated Measure ANOVA show significant interaction.
5) Pearson correlation analysis was done to understand the correlation between the age and the latency of the sustained responses.

4.1 Effect of repetition rate and age (young and older adult group) on the latency of click evoked ABR

The latency of wave V was analyzed for the click evoked ABR across the three different repetition rates (9.1, 19.1 & 40.1/sec). Figure- 4.1 shows an ABR waveform elicited by click at three repetition rates in normal hearing young adult.

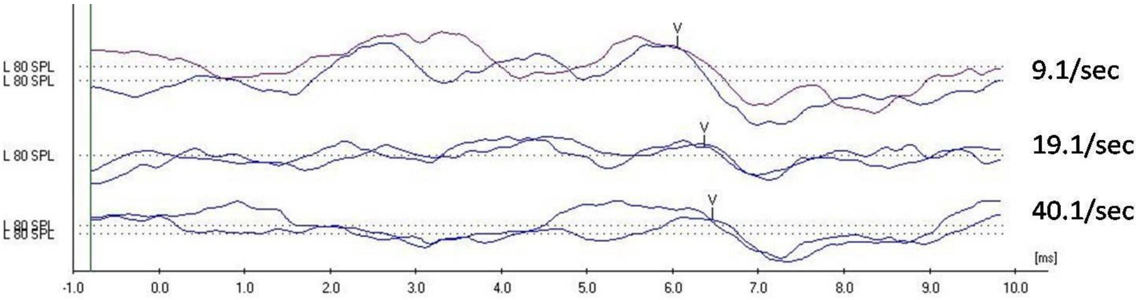

Figure 4.1 A sample waveform of click evoked ABR recorded at three different repetition rates in a young adult.

It can be seen in the figure 4.1 that there is an increase in latency of the click evoked wave V as the repetition rate increased. The mean and the standard deviation (SD) of the wave V latency were calculated for the click evoked ABR recorded at three repetition rates. The mean and the SD values obtained are given in table 4.1.

Table 4.1

Mean and S.D. of click evoked ABR wave V latency obtained at three repetition rates(RR) for young and older adult group.

RR	Young Age Group		Older adult Group	
	Mean latency (msec)	SD (msec)	Mean latency (msec)	SD (msec)
9.1/s	5.93	0.24	6.43	0.33
19.1/s	6.08	0.29	6.52	0.33
40.1/s	6.30	0.24	6.72	0.35

It can be seen from the table 4.1 that as the repetition rate increased, there is an increase in mean latency of the wave V elicited by click for both the groups.

To see the effects of repetition rate on latency of click evoked ABR wave V, Mixed ANOVA was done. Mixed ANOVA revealed a significant main effect for three repetition rates [F (2,116) = 126.11, $p<0.05$], but Mixed ANOVA failed to show any significant interaction between the repetition rates and the two groups [F (2,116) = 1.94, $p>0.05$]. Mixed ANOVA also showed a significant difference for the two groups [F (1, 58) = 40.77, $p<0.05$]. Bonferroni pairwise comparison test was done to see the groupwise differences for the three repetition rates. Details of the pairwise comparison test are shown in table 4.2

Table 4.2

Bonferroni pairwise comparison test results for the wave V latency of the click evoked ABR across the three repetition rates.

Repetition Rates ↓ →	10.9	15.4
6.9	$p<0.05$	$p<0.05$
10.9		$p<0.05$

As the Mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, Repeated Measure ANOVA (3 repetition rates) was done within the young and older adult group to see which group had significant difference in click elicited wave V latency across the repetition rates. Repeated measure ANOVA test results showed that there was significant difference across the three repetition rates for the young group [F (2, 58) = 66.71, $p<0.05$] and for the older adult group [F (2, 58) = 60.18, $p<0.05$]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for the young and older adult group, Bonferroni post hoc test was done to see the significant differences for wave V of click latency across 3 repetition rates. Details of the Bonferroni post hoc test across the three repetition rates for young and older adult group is shown in table 4.3

Table 4.3

Bonferroni post hoc test results for the wave V latency of the click evoked ABR across the three repetition rates for young and older adult group.

Group	Repetition Rates ↓ →	19.1	40.1
Young age group	9.1	p<0.05	p<0.05
	19.1		p<0.05
Older adult group	9.1	p<0.05	p<0.05
	19.1		p<0.05

4.2 Effect of Repetition Rate and age (young and older adult group) on the latency of speech evoked ABR

The latency of wave V, A, D, E, F was analyzed for the speech evoked ABR for three different repetition rates (6.9, 10.9, and 15.4). Figure 4.2 shows syllable /da/ evoked ABR and FFR waveform at three repetition rates obtained from one of the young group individual.

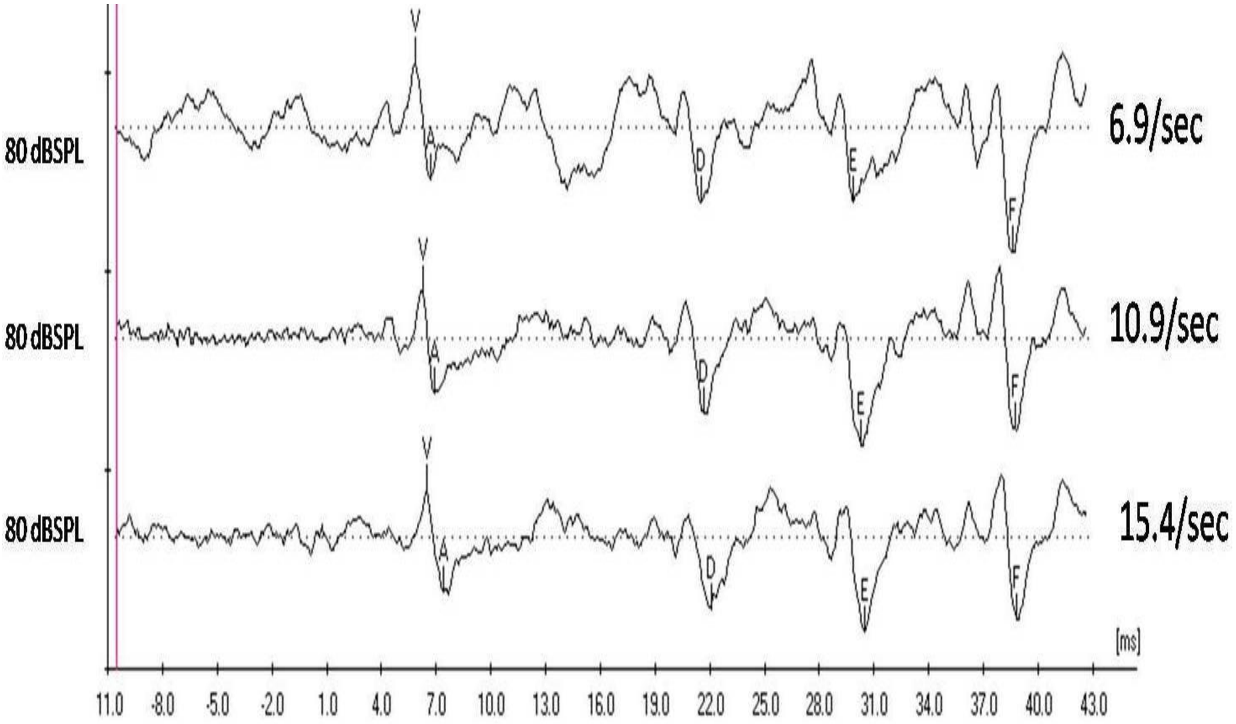

Figure 4.2 A sample waveform of Speech evoked ABR- transient and FFR waveform at three repetition rates obtained from one young group individual.

As it can be seen in the figure 4.2 that there is an increase in latency of all the peaks of speech evoked transient response (wave V and wave A) and FFR (wave D, E and F) with the increase in repetition rate. The mean and standard deviations for the latency of different peaks of speech evoked auditory brainstem responses was calculated and are given in table 4.4

Table 4.4

Mean and Standard Deviation (SD) of latencies of different peaks of speech ABR.

	Wave	**Repetition Rate**	**Young Age Group**		**Older adult Group**	
			Mean latency (msec)	SD (msec)	Mean latency (msec)	SD (msec)
	Wave V	6.9	5.93	0.17	6.20	.36
Transient Responses		10.9	6.31	0.20	6.54	0.34
		15.4	6.63	0.27	6.84	0.45
	Wave A	6.9	6.76	0.29	7.00	0.39
		10.9	7.08	0.24	7.34	0.41
		15.4	7.50	0.34	7.65	0.47
	Wave D	6.9	21.83	0.67	21.85	1.12
		10.9	21.98	0.83	21.97	1.12
Sustained Responses		15.4	22.23	0.87	22.32	1.34
	Wave E	6.9	30.13	0.37	30.66	0.86
		10.9	30.41	0.35	30.86	0.86
		15.4	30.70	0.33	31.09	0.81
	Wave F	6.9	38.81	0.46	38.93	1.40
		10.9	38.98	0.45	39.37	0.54
		15.4	39.16	0.43	39.47	0.61

It can be seen from the table 4.4 that, as the repetition rates increased, there is an increase in mean latency of all the peaks of speech evoked transient response and sustained responses.

To understand the significant difference for the three repetition rates for the latency of wave V, A D, E and F of speech evoked ABR, Mixed ANOVA was done. Mixed ANOVA revealed a significant main effect for the three repetition rates for the latency of wave V, A D, E and F of speech evoked ABR [F (2, 116) = 155.34, p< 0.05], but Mixed ANOVA failed to show any significant interaction between repetition rates and groups [F (2, 116) = 0.17 p> 0.05]. Mixed ANOVA revealed a significant difference across the two groups [F (1, 58) = 4.78, p< 0.05]. Bonferroni pairwise comparison was done to see the groupwise differences for the three repetition rate. Details of the pairwise comparison is shown in table 4.4

Table 4.5

Bonferroni pairwise comparison results for the /da/ evoked speech ABR across the three repetition rates.

Repetition Rates ↓ →	10.9	15.4
6.9	p<0.05	p<0.05
10.9		p<0.05

Onset responses (Wave V and Wave A): As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave V and wave A latency across the repetition rates. Repeated measure ANOVA test results showed that for wave V latency, there was a significant difference across the three repetition rates for younger group [F(2, 58)= 292.93, p< 0.05] and the older adult group [F(2, 58)= 169.50, p< 0.05] and for wave A latency also, there was a significant difference across the three repetition rates for younger group [F(2, 58)= 115.05, p< 0.05] and the older adult group [F(2, 58)= 107.85, p< 0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for both the groups, Bonferroni post hoc test was done to see, at which two repetition rates, latency differed significantly for wave V and wave A. The results obtained from the Bonferroni post hoc test for wave V and wave A across the three repetition rates for young and older adult group are shown in table 4.6

Table 4.6

Bonferroni post hoc test results for the /da/ evoked wave V and A latency across the three repetition rates for young and older adult group.

Group	Repetition Rates	10.9	15.4
Young age group	6.9	p<0.05	p<0.05
	10.9		p<0.05
Older adult group	6.9	p<0.05	p<0.05
	10.9		p<0.05

Sustained Responses -Wave D: As the Mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, Repeated Measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave D latency across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rates for younger group [F (2, 58) = 18.39, p< 0.05] and the older adult group [F (2, 58) = 9.22, p< 0.05]. As the Repeated

Measure ANOVA showed significant difference across the repetition rates for both the groups, Bonferroni post hoc test was done to see, at which two repetition rates wave D latency, differed significantly. The results obtained from the Bonferroni post hoc test across the three repetition rates for young and older adult group is shown in table 4.7

Table 4.7

Bonferroni post hoc test results for the /da/ evoked wave D latency across the three repetition rates for young and older adult group.

Group	Repetition Rates ↓ →	10.9	15.4
Young age group	6.9	p>0.05	p<0.05
	10.9		p<0.05
Older adult group	6.9	p>0.05	p<0.05
	10.9		p<0.05

Since, the wave V latency increased with increase in repetition rate, the delay in wave D might be due to delay in wave V. To understand whether the delay in wave D was because of increase in latency of wave V or repetition rate affected the wave D latency, the wave D latency was covaried for 10.9 & 15.4 repetition rate with respect to 6.9/sec. A repeated measure ANOVA showed a siginificant difference across the repetition rates for the young group [F(2, 58)= 11.87, p< 0.05] but failed to show a significant difference for the older adult group [F(2, 58)= 1.71, p> 0.05]. For the young group, Bonferroni post hoc test was done and a significant difference was found between 6.9/sec and 10.9/sec (p<0.05), between 6.9/sec & 15.4/sec (p<0.05) but not between 10.9/sec & 15.4/sec (p>0.05).

Sustained Responses -Wave E: As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave E latency across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rates for younger group [$F(2, 58)= 40.14$, $p< 0.05$] and the older adult group [$F(2, 58)= 10.62$, $p< 0.05$]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for both the groups, Bonferroni post hoc test was done to see, at which two repetition rates wave E latency, differed significantly. The results obtained from Bonferroni post hoc test across the three repetition rates for young and older adult group is shown in table 4.8

Table 4.8

Bonferroni post hoc test results for the /da/ evoked wave E latency across the three repetition rates for young and older adult group.

Group	Repetition Rates ↓ →	10.9	15.4
Young age group	6.9	$p<0.05$	$p<0.05$
	10.9		$p<0.05$
Older adult group	6.9	$p>0.05$	$p<0.05$
	10.9		$p<0.05$

Since, the wave V latency increased with increase in repetition rate, the delay in wave E might be due to delay in wave V. To understand whether the delay in wave E was because of increase in latency of wave V or repetition rate affected the wave E latency, the wave E latency was covaried for 10.9 & 15.4 repetition rate with respect to 6.9/sec. A repeated measure ANOVA failed to show any significant difference across the repetition rates for the young group [F (2, 58)= 1.97, p> 0.05] and for the older adult group [F(2, 58)= 2.41, p> 0.05].

Sustained Responses -Wave F: As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave F latency across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rates for younger group [F(2, 58)= 44.33, p< 0.05] and the older adult group [F(2, 58)= 3.39, p< 0.05]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for both the groups, Bonferroni post hoc test was done to see, at which two repetition rates wave F latency, differed significantly. The results obtained from the Bonferroni post hoc test across the three repetition rates for young and older adult group is shown in table 4.9

Table 4.9

Bonferroni post hoc test results for the /da/ evoked wave F latency across the three repetition rates for young and older adult group.

Group	Repetition Rates ↓ →	10.9	15.4
Young age group	6.9	p<0.05	p<0.05
	10.9		p<0.05
Older adult group	6.9	p>0.05	p>0.05
	10.9		p>0.05

Since, the wave V latency increased with increase in repetition rate, the delay in wave F might be due to delay in wave V. To understand whether the delay in wave F was because of increase in latency of wave V or repetition rate affected the wave F latency, the wave F latency was covaried for 10.9 & 15.4 repetition rates with respect to 6.9/sec repetition rate. A repeated measure ANOVA showed a significant difference across the repetition rates for the young group [F(2, 58)= 26.62, p< 0.05] but failed to show any significant difference for the older adult group [F(2, 58)= 0.43, p> 0.05]. For the young group, Bonferroni post hoc test was done and a significant difference was found between 6.9/sec and 10.9/sec (p<0.05), between 6.9/sec & 15.4/sec (p<0.05) and between 10.9/sec & 15.4/sec (<0.05).

4.3 Effect of repetition rate and age (young and older adult group) on the amplitude of pitch and harmonics of speech evoked ABR

The amplitude of F0 (103 to 125 Hz), F1 (220 to 720 Hz) and higher harmonics (F2-1700 to 1240 Hz) was analyzed for the speech evoked ABR for three different repetition rates (6.9, 10.9, 15.4/s). The mean and the SD of the amplitude of F0, F1 and F2 were calculated for the speech evoked FFR recorded at three repetition rates. The mean and the SD values obtained are given in table 4.10

Table 4.10

Mean and the SD of F0, F1 and F2 amplitude elicited by syllable /da/ obtained at three repetition rates across the groups

Parameters ↓	**Repetition Rate**	**Young Age Group**		**Older adult Group**	
		Mean amp (µV)	SD(µV)	Mean amp (µV)	SD (µV)
F0	6.9	5.45	2.09	3.87	1.93
	10.9	4.30	2.02	3.22	1.76
	15.4	4.00	2.06	3.22	1.82
F1	6.9	0.60	0.17	0.43	0.18
	10.9	0.54	0.17	0.40	0.16
	15.4	0.45	0.09	0.38	0.15
F2	6.9	0.34	0.10	0.25	0.07
	10.9	0.27	0.08	0.21	0.07
	15.4	0.26	0.09	0.23	0.08

It can be seen from the table 4.10 that, as the repetition rate increased, there is a general trend of decrease in amplitude of the F0, F1 and F2 of the speech evoked FFR.

To see the significant difference across three repetition rates on F0, F1 and F2 mean amplitude, Mixed ANOVA (3 repetition rates and 2 groups) was done. Mixed ANOVA revealed a significant main effect across the repetition rates [F (2, 116) = 7.58, $p< 0.05$], but Mixed ANOVA failed to show any significant interaction between the repetition rates and the two groups [F (2, 116) = 1.01, $p> 0.05$]. Mixed ANOVA revealed a significant difference across two groups [F (1, 58) = 13.66, $p< 0.05$]. Bonferroni pairwise comparison was done to see the group wise differences for the three repetition rates. Details of the pairwise comparison is shown in table 4.11

Table 4.11

Bonferroni pairwise comparison results for the amplitude of F0, F1 and F2 of /da/ evoked ABR across the three repetition rates.

Repetition Rates ↓ →	10.9	15.4
6.9	$p<0.05$	$p<0.05$
10.9		$p>0.05$

4.3.1 Amplitude of F0- Pitch measure

As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in F0 amplitude across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rate for younger group [$F(2, 58)= 4.93$, $p< 0.05$], but failed to show a significant difference for the older adult group [$F(2, 58)= 1.40$, $p> 0.05$]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for the young group, Bonferroni post hoc test was done to see, which two repetition rates, the F0 amplitude differed significantly. The results obtained from the Bonferroni post hoc test across the three repetition rates for young age group is shown in table 4.12

Table 4.12

Bonferroni post hoc test results for the /da/ evoked F0 amplitude across the three repetition rates for young age group.

Group	Repetition Rates ↓→	10.9	15.4
Young age group	6.9	p>0.05	p<0.05
	10.9		p>0.05

4.3.2 Amplitude of F1 & F2- Harmonic measure

4.3.2.1 Amplitude of F1:

As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in F1 amplitude across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rates for younger group [F(2, 58)= 20.41, p< 0.05] but not in the older adult group [F(2, 58)= 1.88, p> 0.05]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for the young group, Bonferroni post hoc test was done to see, at which two repetition rates, the F1 amplitude differed significantly. The results obtained from the Bonferroni post hoc test across the three repetition rates for young age group is shown in table 4.13

Table 4.13

Bonferroni post hoc test results for the /da/ evoked F1 amplitude across the three repetition rates for young age group.

Group	Repetition Rates ↓→	10.9	15.4
Young age group	6.9	p<0.05	p<0.05
	10.9		p<0.05

4.3.2.2 Amplitude of F2:

As the mixed ANOVA showed significant interaction across the repetition rates, taking data from both the groups, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in F2 amplitude across the repetition rates. Repeated Measure ANOVA test results showed that there is a significant difference across the three repetition rates for younger group [F(2, 58)= 14.15, $p < 0.05$] and in the older adult group [F(2, 58)= 4.87, $p<0.05$]. As the Repeated Measure ANOVA showed significant difference across the repetition rates for the young group, Bonferroni post hoc test was done to see, at which two repetition rates, the F2 amplitude differed significantly. The results obtained from the Bonferroni post hoc test across the three repetition rates for young and older adult group is shown in table 4.14

Table 4.14

Bonferroni post hoc test results for the /da/ evoked F2 amplitude across the three repetition rates for young and older adult group.

Group	Repetition Rates ↓ →	10.9	15.4
Young age group	6.9	$p<0.05$	$p<0.05$
	10.9		$p>0.05$
Older adult group	6.9	$p<0.05$	$p>0.05$
	10.9		$p>0.05$

4.4 Latency of click ABR across the young and older adults:

The following figure 4.3 shows the mean latency of wave V peak latency of click ABR for three repetition rates across the two groups.

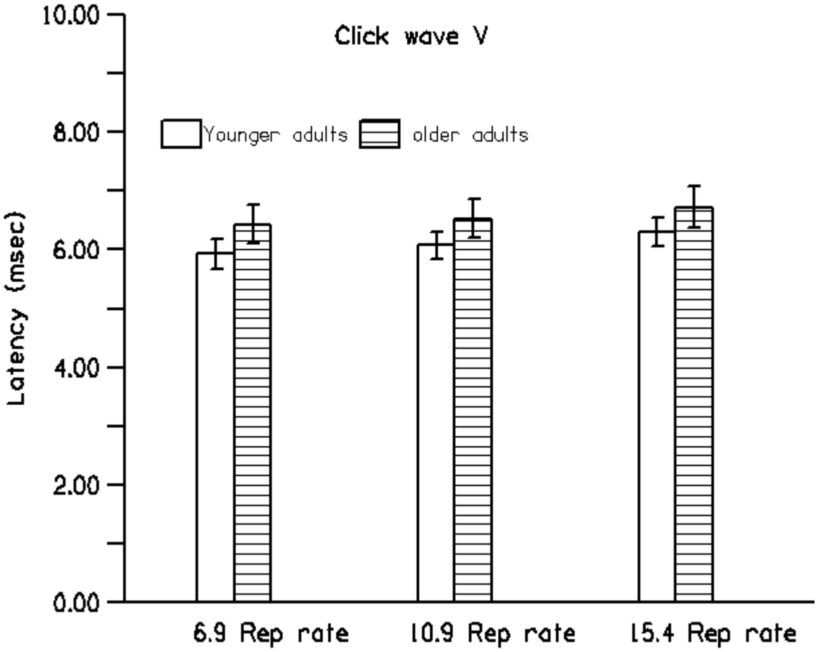

Figure 4.3 Mean latency of wave V peak latency of click ABR for three repetition rates across the two groups.

It can be seen from the figure 4.3 that at all the three repetition rates, the mean latency of wave V of click ABR for older adult group was more prolonged than the young age group. Multiple analysis of variance (MANOVA) was done to understand the significant difference in latency of wave V of click ABR for the two groups across the three repetition rates. MANOVA results showed significant difference in wave V latency of click ABR across the two groups for repetition rate 9.1 [F (1, 58) = 44.013, $p < 0.05$], 19.1 [F (1, 58) = 36.718, $p < 0.05$], 40.1 [F (1, 58) = 30.169, $p < 0.05$].

4.5 Latency of speech evoked ABR across the young and older adult groups:

4.5.1 Latency of onset response

Wave V: The following figure 4.4 shows the mean latency of speech evoked transient V peak latency for three repetition rates across the two groups.

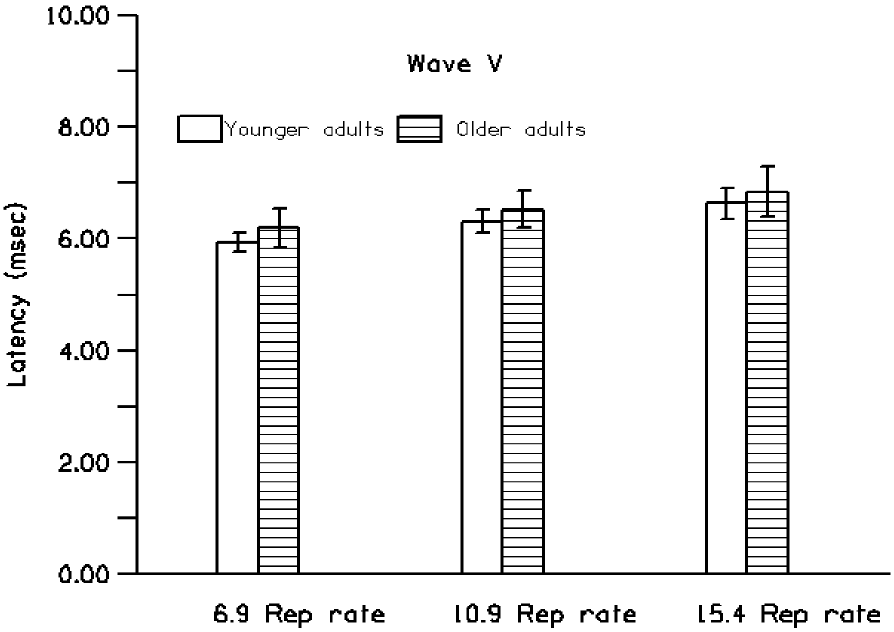

Figure 4.4 Latency of speech evoked transient V peak latency for three repetition rates across the two groups.

It can be seen from the figure 4.4 that at all the three repetition rates, the latency of wave V for older adult group was more prolonged than the young age group. Multiple analysis of variance was done to see the significant difference in latency of wave V across the young and the older adultd groups. MANOVA results showed significant difference in wave V latency of speech ABR across the groups for repetition rate 6.9 [F (1, 58) = 13.70, p< 0.05], 10.9 [F (1, 58) = 9.96, p< 0.05], 15.4 [F(1, 58) = 4.83, p< 0.05].

Wave A: The following figure 4.5 shows the mean latency of speech evoked transient A peak latency for three repetition rates across the two groups.

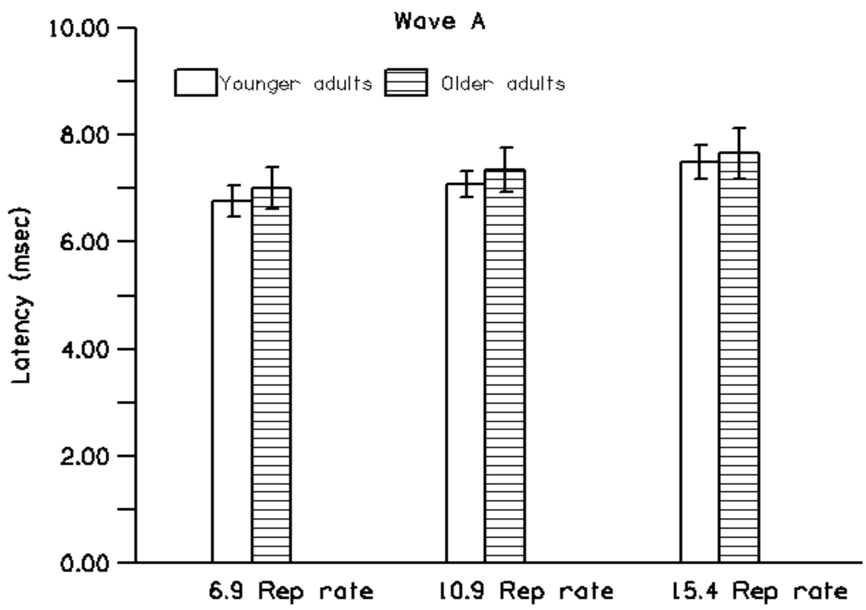

Figure 4.5 Latency of speech evoked transient A peak latency for three repetition rates across the two groups.

It can be seen from the figure 4.5 that at all the three repetition rates, the latency of wave A for older adult group was more compared to the young age group. Multiple analysis of variance was done to see the significant difference in latency of wave A across the young and the older adultd groups. MANOVA results showed significant difference in wave A latency of speech ABR across the groups for repetition rate 6.9 [F(1, 58)= 7.40, $p < 0.05$], 10.9 [F(1, 58)= 8.92, $p < 0.05$] , but no significant difference for repetition rate 15.4 [F(1, 58)= 2.14, $p > 0.05$].

4.5.2 Latency of sustained response of speech evoked ABR across the groups:

Wave D: The following figure 4.6 shows the mean latency of D peak for three repetition rates across the two groups.

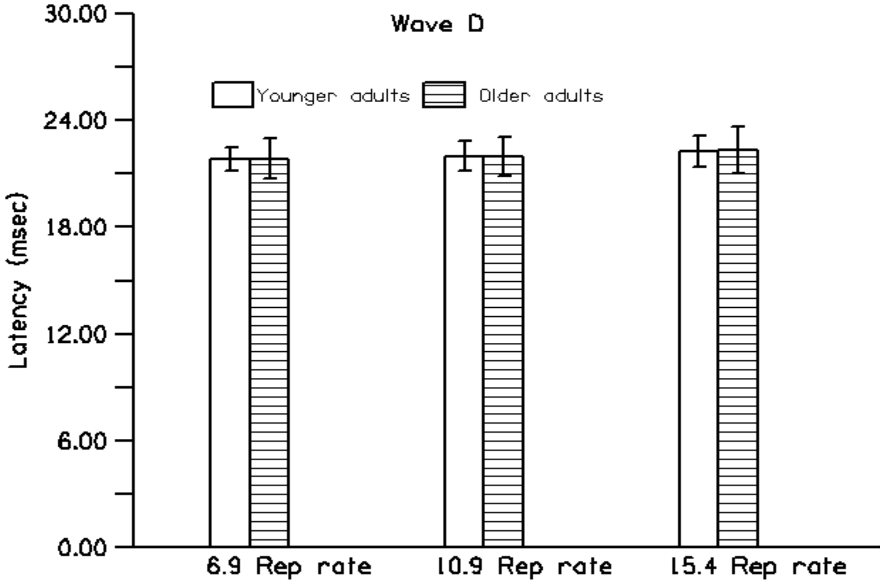

Figure 4.6 Latency of speech evoked D peak latency for three repetition rates across the two groups.

It can be seen from the figure 4.6 that at all the three repetition rates, the mean latency of wave D for older adult group is almost similar to the young age group. Multiple analysis of variance was done to see the significant difference in latency of wave D across the young and the older adultd groups. MANOVA results showed no significant difference in wave D latency in both the groups for repetition rate 6.9 [F (1, 58)= 0.005, p> 0.05], 10.9 [F(1, 58)= 0.001, p> 0.05] and 15.4 [F(1, 58)= 0.097, p> 0.05].

Latency of wave D was covaried for 10.9 & 15.4 repetition rates with respect to 6.9/sec repetition rate in order to understand the significant difference in wave D was due to wave V prolongation or there was an actual delay in wave D at higher repetition rate. Multiple analysis of variance was done with the covaried values of 10.9 and 15.4 repetition rates with respect to the latency of wave V of 6.9 repetition rate. MANOVA results showed no significant difference in wave D latency for the 10.9/sec [F (1, 58) = 0.02, p> 0.05] and for 15.4/sec [F (1, 58) = 0.27, p> 0.05] between the young and older adult groups for the covaried values.

Wave E: The following figure 4.7 shows the mean latency of E peak for three repetition rates across the two groups.

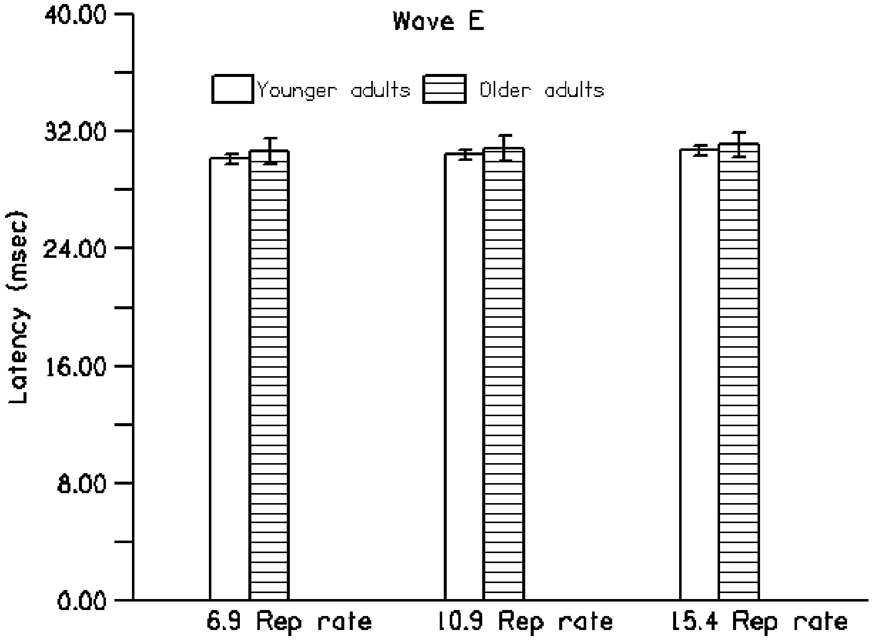

Figure 4.7 Latency of speech evoked E peak latency for three repetition rates across the two groups.

It can be seen from the figure 4.7 that at all the three repetition rates, the mean latency of wave E for older adult group was more prolonged than the young age group.

MANOVA was done to see the significant difference in latency of wave E across the young and the older adult groups. MANOVA results showed significant difference in wave E latency in both the groups for repetition rate 6.9 [F (1, 58) = 9.89, p< 0.05], 10.9 [F (1, 58) = 7.23, p<0.05] and 15.4 [F(1, 58)= 5.98, p< 0.05]. Latency of wave E was covaried for 10.9 & 15.4 repetition rates with respect to 6.9/sec repetition rate in order to understand the significant difference in wave E was due to wave V prolongation or there was an actual delay in wave E at higher repetition rate. Multiple analysis of variance was done with the covaried values of 10.9 and 15.4 repetition rates with respect to the latency of wave V of 6.9 repetition rate. MANOVA results showed a significant difference in wave E latency for the 10.9/sec [F (1, 58) = 7.78, $p < 0.05$] and for 15.4/sec [F (1, 58) = 7.89, $p < 0.05$].

Wave F: The following figure 4.8 shows the mean latency of F peak for three repetition rates across the two groups.

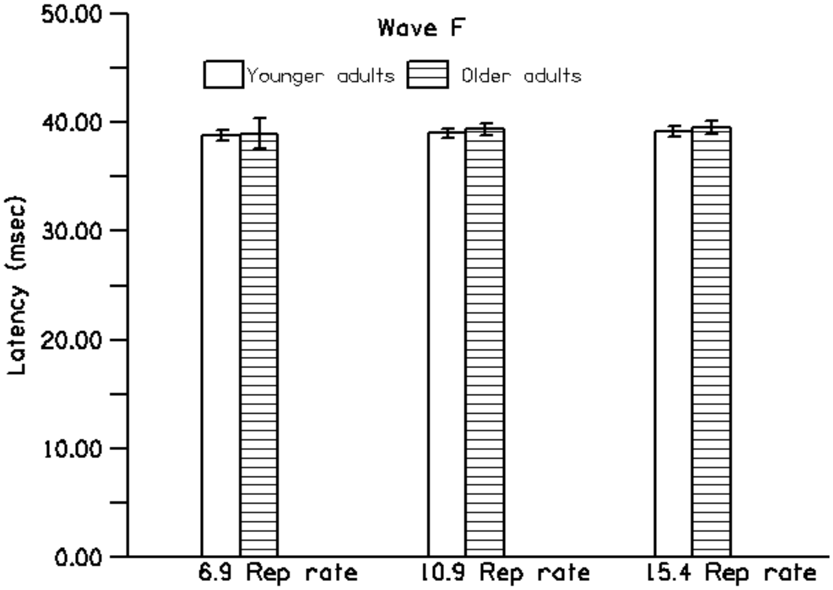

Figure 4.8 Latency of speech evoked F peak latency for three repetition rates across the two groups.

It can be seen from the figure 4.8 that at all the three repetition rates, the mean latency of wave F for older adult group was more prolonged than the young age group.

MANOVA results showed no significant difference in wave F latency in both the groups for repetition rate 6.9 [F (1, 58) = 0.18, $p > 0.05$], but showed significant for 10.9 [F

(1, 58) = 9.197, $p<0.05$] and 15.4 [F (1, 58) = 5.250, $p< 0.05$]. Latency of wave F was covaried for 10.9 & 15.4 repetition rates with respect to 6.9/sec repetition rate in order to understand the significant difference in wave F was due to wave V prolongation or there was an actual delay in wave F at higher repetition rate. Multiple analysis of variance was done with the covaried values of 10.9 and 15.4 repetition rates with respect to the latency of wave V of 6.9 repetition rate. MANOVA results showed significant difference in wave F latency for the 10.9/sec [F(1, 58)= 10.36, $p< 0.05$] and for 15.4/sec [F(1, 58)= 8.84, $p<0.05$].

4.6 Amplitude of the F0, F1 and Higher Harmonics (F2) across the young and older adult groups:

4.6.1 Amplitude of F0: The mean amplitude of F0 comparing between young and older adult group is shown in the figures 4.9

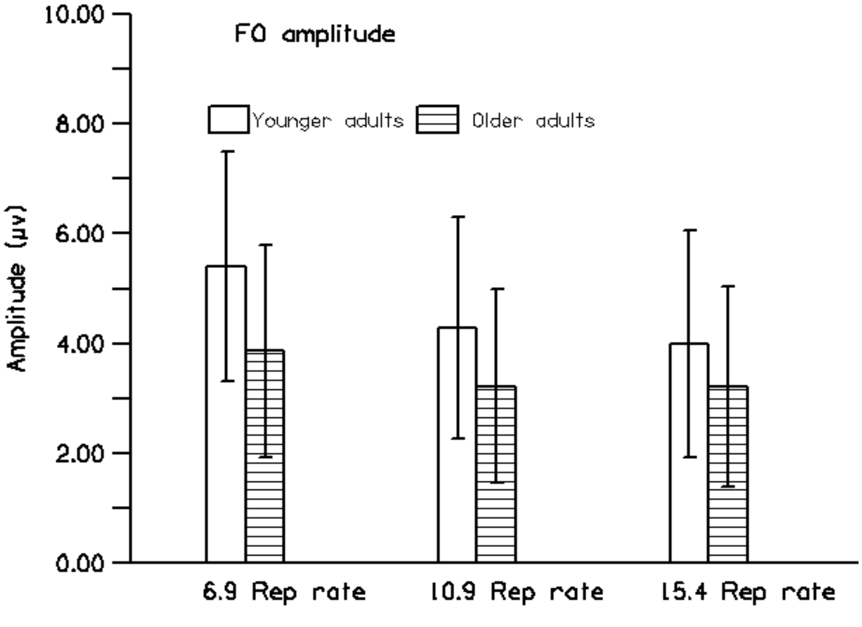

Figure 4.9 Amplitude of F0 at 6.9, 10.9 and 15.4 repetition rates across the two groups.

It can be seen from the figure 4.9 that at all the three repetition rates, the F0 amplitude of older adult group was lesser than young age group. Multiple analysis of variance was done to understand the significant difference for the amplitude of F0 between the young and the older adult group. MANOVA results showed significant difference in F0 amplitude in both the groups for repetition rate 6.9 [F(1, 58)= 8.902, p<0.05], 10.9 [F(1, 58)= 4.799, p<0.05] , but showed no significant difference for repetition rate 15.4 [F(1, 58)= 2.402, p> 0.05].

4.6.2 Amplitude of F1: The mean amplitude of F1 comparing between young and older adult group is shown in the figures 4.10

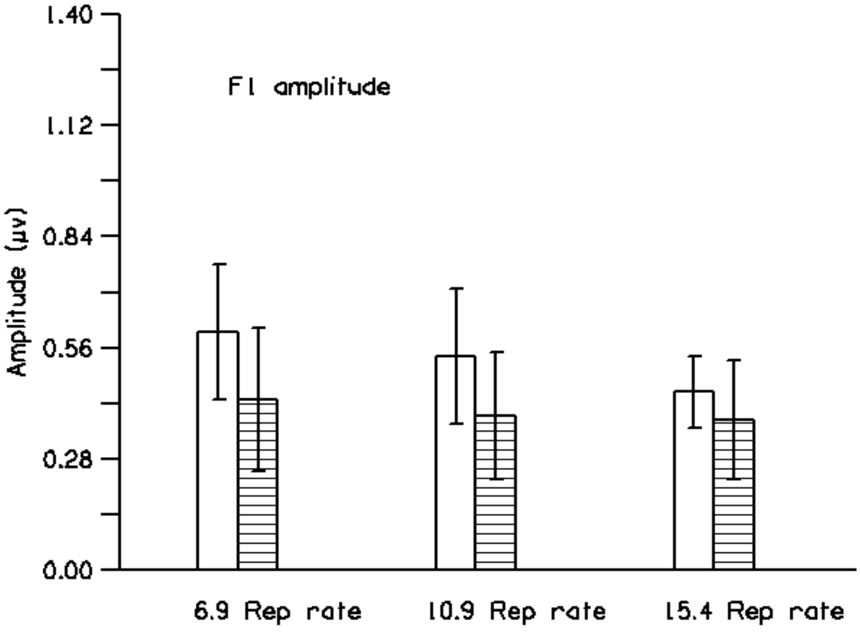

Figure 4.10 Amplitude of F1 at 6.9, 10.9 and 15.4 repetition rates across the two groups.

It can be seen from the figure 4.10 that at all the three repetition rates, the F1 amplitude of older adult group was lesser than young age group.

Multiple analysis of variance was done to understand the significant difference for the amplitude of F1 between the young and the older adult group. MANOVA results showed significant difference in F1 amplitude in both the groups for repetition rate 6.9 [F(1, 58)= 13.665, p<0.05], 10.9 [F(1, 58)= 11.048, p<0.05] , 15.4 [F(1, 58)= 5.069, p> 0.05].

4.6.3 Amplitude of F2: The mean amplitude of F2 comparing between young and older adult group is shown in the figures 4.11

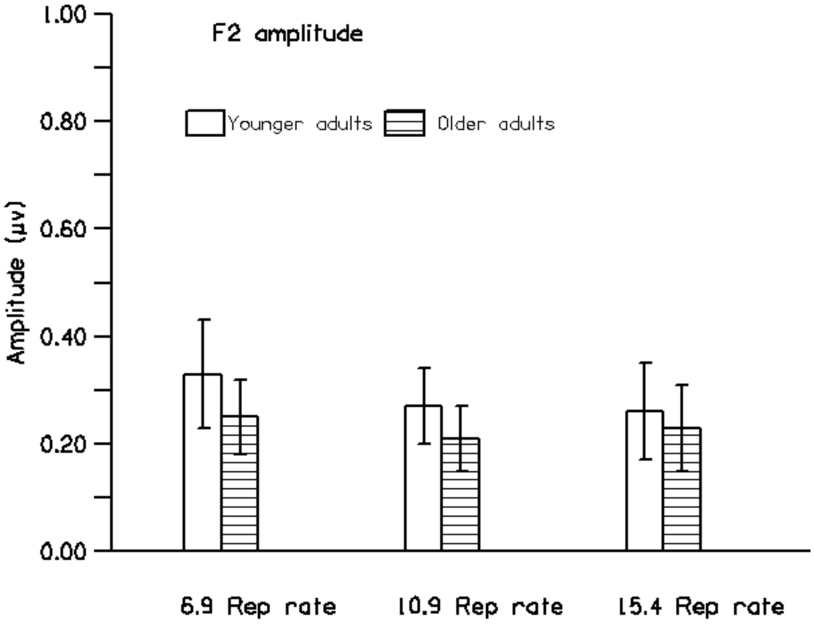

Figure 4.11 Amplitude of F2 at 6.9, 10.9 and 15.4 repetition rates across the two groups.

It can be seen from the figure 4.11 that at all the three repetition rates, the F2 amplitude of older adult group was lesser than young age group.

Multiple analysis of variance was done to understand the significant difference for the amplitude of F2 between the young and the older adultd group. MANOVA results showed significant difference in F2 amplitude in both the groups for repetition rate 6.9 [F(1, 58)= 12.999, p<0.05], 10.9 [F(1, 58)= 10.323, p<0.05] , but no significant difference for 15.4 [F(1, 58)= 2.023, p> 0.05].

4.7 Pearson Correlation between age and sustained components:

In MANOVA, after covarying it with respect to wave V, it was found that for wave D, there was no significant difference across the groups, whereas a significant difference was found for peak E & F. So to understand the significant difference, a correlational analysis was done where age was the independent variable and wave D, E & F were the dependent variables. Correlation analysis reveals the following results in figure 4.12 in terms of scatter plot.

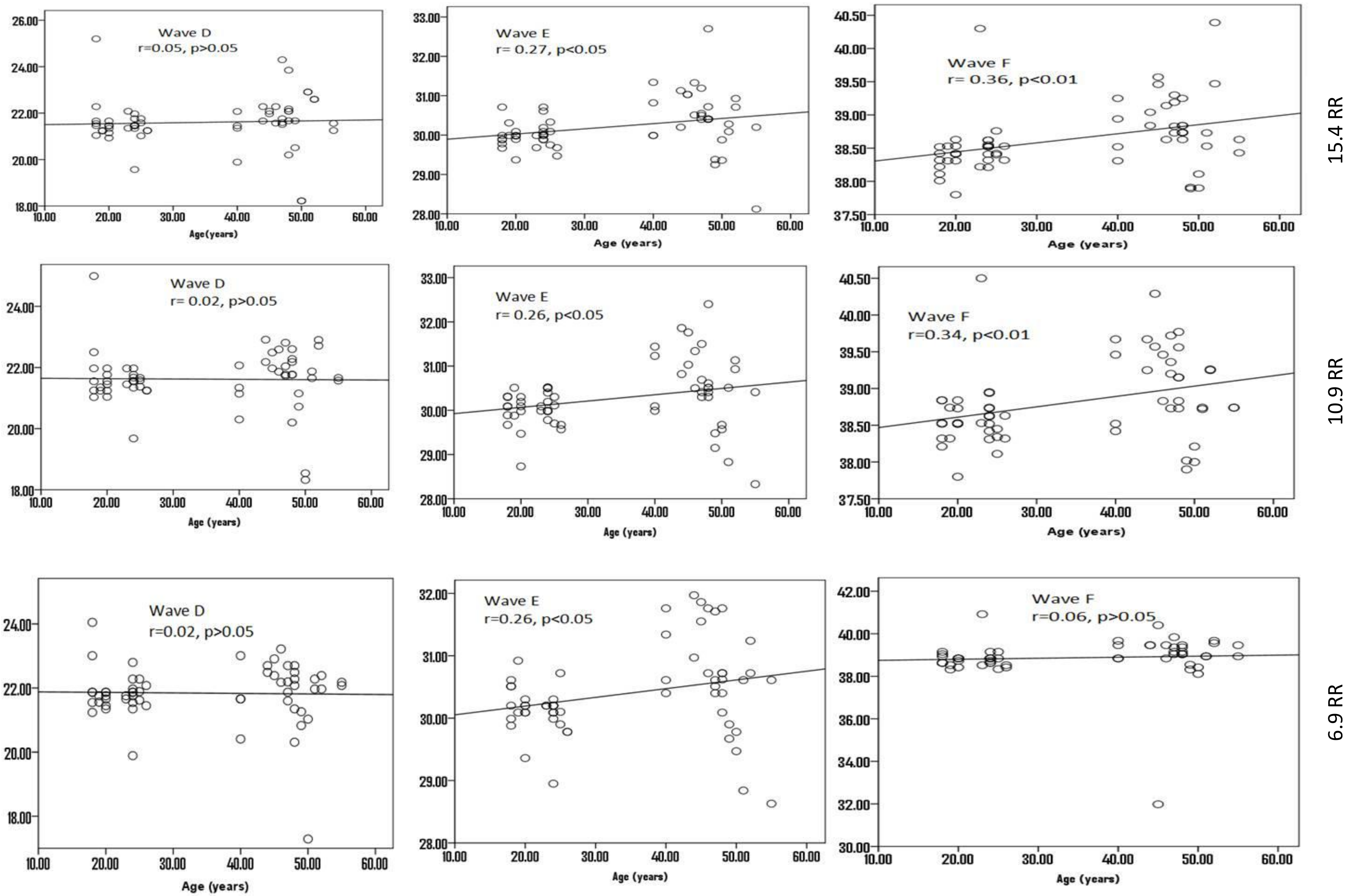

Figure 4.12 Correlation analysis between the age and the latency of the frequency following responses (sustained responses)

To summarize:

The click evoked wave V latency increased with increase in repetition rate for both the groups and this prolongation in latency was more for the older adult group compared to the young age group at all the repetition rates.

The speech evoked onset response (wave V and wave A) latency increased with increase in repetition rate for both the groups and this prolongation in latency was more for the older adult group compared to the young age group. For the sustained response, latency increased for wave D, E and F with increase in repetition rate for young group and for wave E and F for older adult group and the prolongation in latency of wave E and F was more for the older adult group compared to the young age group. When the sustained response was covaried with wave V, the rate effect disappeared for wave E latency in young age group and for wave D & E in older adult group. After correction of sustained response, the prolongation in latencies of wave E & F was more for the older adult group compared to young age group.

The FFT- amplitude of F0, F1 and higher harmonics (F2) decreased with increase in repetition rate for the young group and for F2 amplitude in older adult group and this reduction in amplitude for F0, F1 and higher harmonics (F2) was more for the older adult group compared to the young age group.

Chapter 5

Discussion

The present study was conducted with an aim of studying the brainstem correlates of the auditory temporal processing in the young age and older adult adults with normal hearing sensitivity. This was done by recording speech and click evoked ABR at different repetition rates. The two stimuli were chosen as they differ significantly in their acoustic properties.

Effect of repetition rate on latency of onset response of click ABR and speech evoked ABR

With increase in repetition rate, the latencies of click evoked ABR wave V and speech evoked ABR onset response – wave V & A were prolonged for both the groups and more prolongation was seen for the older adult group compared to young age group.

Present study is supports the earlier studies which report a prolongation in latency with increase in repetition rate (Thornton & Coleman 1975; Don, Allen & Starr, 1977; Yagi & Kaga 1979; Lasky, 1984, 1997; Burkard & Hecox 1983, 1987a, 1987b). Burkard and Sims (2001) reported that with increasing click rate, peak latencies increased, the I–V interval increased and peak amplitudes decreased in both young and older normal individuals. Mamatha and Barman (2008) reported that the latencies of wave I, III and V increased with increase in repetition rate within the age groups from 30 to 65 years.

However, there are studies which report that there is no change in latency of click evoked ABR with increase in repetition rate up to 20/sec (Jewett, Romano & Williston, 1970; Krizman, Skoe & Kraus, 2010). Fowler and Noffsinger (1983) also reported no change in latency of click evoked ABR waves with increase in repetition rate between 2- 20 Hz. However, in present study a significant difference was obtained between 9.1/sec, 19.1/sec and 40.1/sec repetition rates. The difference reported in the present study might be due to the methodological differences between the present and the earlier studies. Earlier studies have been utilized either 80 dB nHL or 90 dB nHL intensity to record auditory brainstem responses whereas, the present study has been done at 80 dB SPL intensity.

With respect to the onset response of the speech evoked ABR, several authors have reported an increase in the onset response with the increase in repetition rate of the stimuli in adults (Krizman, Skoe & Kraus, 2010) and in children (Ranjan, 2011, Mehta & Singh, 2012). The increase in latency of wave V of click ABR and wave V and A of speech evoked ABR due to increase in the repetition rate might be due to cumulative neural fatigue and adaptation, and incomplete recovery involving hair-cell-cochlear nerve junction and also subsequent synaptic transmission. Latency shifts seen with increase in rate in normals may also be due to a change in cochlear receptor functions (Don et al., 1977), the refractory period of individual nerve fibers resulting in a desynchronization of the response that most affects the encoding of the faster elements of the stimulus (Hall, 1992; Jacobson, Murray & Deppe, 1987), decrease in synaptic efficiency (Pratt & Sohmer, 1976) due to which conduction rate decreases and there is an increase in latency. The effect of rate would be additive as the synapses increases from wave I to wave V (Hall, 1992).

Another finding of the present study was that the latency of the onset responses was more for 40-55 years age group compared to the 18 to 30 years age group for a higher repetition rate and even at lower repetition rates also. Mamatha & Barman (2008) reported that the latencies of wave I, III and V increased with increase in repetition rate across the age groups from 30 to 65 years and there was a greater increase in the latency for wave III and wave V in older individuals. Patterson, Michalewski, Thompson, Bowmanm and Litzelman (1981) reported that older adults (60 to 79 years) had longer latencies at wave III and wave V compared to the older adults (40 to 59 years) and older adult individuals had longer latencies compared to the young adults (20 to 39 years).

These delayed latencies in the onset of the click and speech evoked ABR with increasing age could be consistent with a reduction in synchronous neural firing to transient changes in stimulus and impaired neural encoding of the onset of a stimulus in the older adult individuals. Akhoun et al. (2008) suggested that the onset response of the ABR particularly reflects the synchronous response of many types of brain stem cells at the levels of the cochlear nucleus and inferior colliculus. Therefore, this portion of the response is likely to be affected by age-related loss in neural synchrony in the central auditory system, which may be independent of changes at the periphery (Boettcher, Mills, Swerdloff & Holley, 1996; Gates, Feeney & Higdon, 2003; Mills, Schmeidt, Schulte & Dubno, 2006; Pichora-Fuller, Schneider & McDonald, 2007). This provides an index for examining the role of subcortical timing and its relationship to normal, impaired and the expert auditory perception.

Further, as the repetition rate increased, the difference was maintained between the two groups i.e the latency was consistently more for the older adult group compared to the younger adults even at higher repetition rate. The neurophysiological mechanisms responsible for observed latency shifts at higher repetition rates in the older adults might be due to taxing the auditory system at higher repetition rates resulting in cumulative neural fatigue and adaptation, and incomplete recovery involving hair-cell-cochlear nerve junction and also subsequent synaptic transmission. These phenomenons might be affected more in older adult individuals compared to the young adults probably because of reduced neural synchrony in older adult individuals. The findings observed at higher repetition rates also suggest an impaired temporal processing in older adults. Behavioral studies have also reported that temporal processing is affected in older adult individuals (Babkoff, Ben- Artzi & Fostick, 2011; Abel, Krever & Alberti, 1990; Grose, Hall & Buss, 2006). Impaired temporal processing in older adults might be due to reduced neural synchrony, slowed neural conduction time, and reduced phase-locking abilities, which might affect the neurons in the central auditory system to accurately encode important temporal features of signal.

These findings suggest that older adults had a general reduction in synchronous neural firing in response to transient information at the onset of a speech and a click stimulus. Thus, one can hypothesize that the degradation in the onset response of the auditory brainstem responses might start in the older adults itself.

Effect of repetition rate on latency of speech evoked FFR- sustained measure

A significant difference was seen in the latency of wave E, F with increase in repetition rate in the young group whereas for wave D, a significant difference was seen only between 6.9/sec & 15.4/sec and 10.9 & 15.4/sec for the young adults. For the older adult group, a significant difference was seen in the latency of wave D and E between 6.9/sec & 15.4/sec and between 10.9/sec & 15.4/sec. No significant difference was found in the latency of wave F for all repetition rates in the older adult group.

When the D, E and F peaks were covaried with wave V, for wave D & F, there was a significant difference in latencies with increase in repetition rate for the young group but not for the older adult group. For peak E, no significant difference was found for both the groups.

A significant difference was obtained in the latency of wave E for all repetition rates and for wave F for repetition rate of 10.9/sec and 15.4/sec across the young adults and older adult group. No significant difference was found in the latency of wave D for all repetition *rates across the groups and similar findings were obtained after covarying the waves D, E & F with respect to wave V.*

As the repetition rate increased, a significant prolongation in the latency of few peaks of sustained responses was obtained for both the young adults as well as the older adult groups. Looking at the prolongation of the wave V latency of speech evoked ABR, it was suspected that the latency prolongation of the sustained responses might be due to the prolongation of wave V with increase in repetition rate. Hence, the peaks of sustained response were covaried with the wave V latency and after covarying, the rate effect disappeared for all the peaks of older adult group suggesting that the shift seen at sustained responses were a carryover of the large effect of rate on wave V latency for the older adult group. However, after covarying the latencies for the young group, there was a significant difference for wave D and wave F but not for wave E. Krizman et al. (2010) have reported no effect of repetition rate on the sustained responses of the speech evoked ABR in younger adults. The present study followed the recording protocol of Krizman et al. (2010). Although the recording protocol was same, the results obtained were different for the two studies. At this point of time it is difficult to define why repetition rate selectively affected the latencies of two peaks of the sustained responses for the young groups.

After covarying the peaks of sustained responses, a significant difference was obtained for E peak between the two groups at all the repetition rates whereas, a significant difference was obtained for the F peak at 10.9 repetition rate and 15.4 repetition rate but not the 6.9 repetition rate and for peak D, there was no difference obtained between the two groups for any of the repetition rate. To understand this, a correlation analysis was done which revealed that there was no correlation between age and wave D latency (i.e as the age increased there was no prolongation in the D peak latency), whereas it revealed a significant correlation for wave E for all the repetition rates and for wave F for 10.9 and 15.4 repetition rate. The differences between the two groups for these peaks suggest a selective prolongation of the wave E and F component of the sustained responses for the older adults.

Clinard, Tremblay and Krishnan (2010) also found some significant age effects for the sustained portion of the S-ABR. Significant correlations with advancing age were reported for latencies of the sustained responses for older adults in the age range of 22- 77 years old. Vander, Kathy, Burns and Kristen (2011) also reported a similar finding for individuals in the age range of 61-78 years. The results of the Clinard et al. (2010) and Vander et al. (2011) are in good general agreement with those of this study.

The neurophysiological mechanism behind the encoding of sustained FFR response is dependent on the integrity of phase locked neural activity in the auditory brainstem (Worden & Marsh, 1968). For the encoding of sustained components (wave E and F), there is a significant difference between the young and older adult group, which suggests a delay in encoding of these components at lower repetition rate for the older adults compared to the young adults at the upper brainstem. The effect continues even at higher repetition rates which suggest a possible reduction in temporal processing in the older adults at the upper brainstem level. Temporal processing is dependent on the neural detection of time-varying acoustic cues which might be affected in older adults as a result of poor neural synchrony (Frisina & Frisina, 1997; Schneider & Pichora-Fuller, 2001).

This effect could result from a reduced neural synchrony in peripheral and/or central auditory changes with age. This delay in latencies reflects disrupted neural synchrony, which may also be related to age-related changes in physiology such as metabolic activity in the cochlea (Mills et al., 2006), levels of inhibitory neurotransmitters (Caspary, Schatteman & Hughes, 2005), or decreased cell counts in auditory nuclei (Frisina & Walton, 2006). Age-related related changes to the capacitance and input resistance of inner hair cells (IHCs) or changes in synapses between IHCs and auditory nerve fibers could also influence the coding of the sustained responses (Moser, Neef & Khimich, 2006). For example, deficits of temporal processing have been found in a group of 40–55 year-old individuals (Grose et al. 2006), reduced gap detection ability in middle-aged women (Helfer et al. 2006), reduced DPOAE amplitudes in normal-hearing middle-aged adults (Dorn et al. 1998), subtle differences in auditory perception between younger and older adult subjects in auditory event-related potential (Alain, McDonald, Ostroff & Schneider, 2004; Geal-Dor, Goldstein, Kamenir & Babkoff, 2006), processing of inter aural phase differences both in behavioral and physiological tasks (Ross, Fujioka, Tremblay & Picton, 2007) demonstrating that age-dependent subtle auditory changes may begin in older adult individuals.

Thus the poorer encoding of periodicity at the brainstem level in terms of FFR suggests that age-related decline tends to start in the mid age itself.

Effect of repetition rate on representation of F0, F1 & F2- Pitch and harmonic measure

For the young age group, a significant difference was seen in the amplitude of F0 for 6.9/sec & 15.4/sec, for F1 at all repetition rate and for F2 between 6.9/sec & 10.9/sec and 6.9/sec & 15.4/sec. For the older adult group, a significant difference was found only in F2 amplitude between 6.9/sec & 10.9/sec whereas no significant difference was found for F0 and F1 amplitude with increase in repetition rate.

A significant difference was seen in the amplitude of F0 and F2 across the groups for 6.9/sec & 10.9/sec and for all repetition rates in the amplitude of F1.

Krizman et al., (2010) reported a significant rate effect on the higher harmonics and not on the coding of F0 and F1. However, in the present study there was a significant effect of repetition rate on encoding of F0, F1 and F2 for younger adults and encoding of F2 in older adults. The results obtained in the present study for the older adult group is similar to Krizman et al. (2010). One thing to be noticed here is that even the repetition rate had greater effect on the latencies of sustained responses for the young group compared to the older adult group. After covarying, in the older adult group, there was no effect of repetition rate on latencies of the sustained responses (wave D, E and F). Since the encoding of the F0, F1 and F2 is dependent upon the sustained responses, the responses obtained here for F0, F1 and F2 might be somehow correlated with the latency of the sustained responses in the young group and older adult group. But this mechanism needs to be further checked with more investigations.

A significant difference was seen in the amplitude of F0 and F2 across the groups for 6.9/sec & 10.9/sec and for all repetition rates in the amplitude of F1. These findings suggest that in the older adult individuals there might be a problem in encoding of these key elements of speech. Vander et al. (2011) also reported reduced phase-locking to the fundamental and harmonic frequency components of speech, as measured by the reduced spectral amplitude for F0, F1, and F2 for individuals in the age range of 22-77 years old. Clinard et al. (2010) also reported a reduction in amplitude of F0 in older individuals.

Reduced encoding of F0, F1 and F2 in older adults is consistent with the interpretation of an age-related decline in phase-locking ability involving the brainstem. However, for the F0 and F1 at 15.4 repetitions rate there was no significant difference obtained between the two groups. This might be due to higher standard deviations recorded for these two components at higher repetition rates. Speech recognition abilities were not assessed in this study; therefore, it is not known whether the age-related differences in coding of F0, F1 and F2 directly relate to difficulty in understanding speech in older adults. It will be of interest to see whether the encoding of F0, F1 and F2 such as those observed in the older adult subjects in this study are correlated with reduced speech perception with and without noise condition. However, in the present study, a relation between the temporal processing abilities in this population and encoding of F0, F1 and F2 was obtained, which suggests that the temporal processing might be affected in the older adult individuals itself.

Chapter- 6

Summary and Conclusion

Perception of acoustic signal depends on accurate encoding of temporal events of auditory signals. The auditory brainstem reflects processing of temporal events those are diagnostically significant in the assessment of hearing loss and neurological function (Hall, 1992). Degenerative changes occur with advancing age in the central auditory pathway, including both sub cortical and cortical structures. Vander, Kathy, Burns & Kristen (2011) reported age related differences in neural processing of speech at the brainstem level. Further, there can be a problem with the coding of speech at the brainstem level if the repetition rate of stimuli is increased. Krizman, Skoe & Kraus (2010) reported that for young normal hearing individuals, subcortical auditory processing gets affected with the increase in stimulus repetition rate for the speech stimuli.

Thus, the study was taken up to investigate the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on click and speech evoked ABR and FFR in older adults with normal hearing sensitivity and to check whether the stimulus rate affects the encoding of the onset of the response or the sustained portion of the response for the speech evoked ABR in young and older adults. Varying the presentation rate, then, manipulates the neurophysiological mechanisms underlying the subcortical encoding of timing, thereby elucidating what happens to the population-wide neural response when the stimulus is manipulated along this temporal dimension.

To accomplish the aim a total of 17 young aged individuals (30 ears) in the age range of 18 to 30 years and 15 older adults (30 ears) in the age range of 40 to 55 years with , both groups with normal hearing sensitivity participated in the study.

To fulfill the participant criterion, pure tone audiometry was done to ensure bilateral normal hearing sensitivity and immittance to rule out middle ear pathology. The subjects were prepared using conventional procedure to record ABR. The brainstem responses to click stimulus was recorded presented at 80 dB SPL across the repetition rates (9.1, 19.1 & 40.1) and was analyzed for wave V latency. The brainstem response to speech evoked ABR was also recorded by using syllable /da/, which was developed by King, Warrier, Hayes & Kraus (2002). The syllable was presented at 80 dB SPL across the three repetition rates (6.9, 10.9 & 15.4). The click evoked ABR was analyzed for wave V and the speech ABR waveforms were analyzed for both the onset (latency of wave V and A) and the sustained (latencies of wave – D, E and F) responses. Fast Fourier Transform were done to find the raw amplitude of F0, F1 and higher harmonics(F2) frequency components elicited by syllable /da/ using custom made program run on a MATLAB platform. The mean and the standard deviation for these parameters were calculated for both the groups at different repetition rates. The data obtained at different repetition rates were analyzed across groups and also within each group.

The data obtained were subjected to statistical analysis using SPSS version 17.0 windows. Mixed ANOVA was done to see the significant interaction across the two groups and five repetition rates. Repeated measure ANOVA was done within the group to see the significant difference in data obtained across the repetition rates. Bonferroni post hoc test was done to see significant difference between the rate for both across groups and also within the group.

The results obtained in the current study can be summarized as follows:

- The click evoked wave V latency increased with increase in repetition rate for both the groups and this prolongation in latency was more for the older adults group compared to the young age group at all the repetition rates. The prolongation in latency was statistically significant for all the three repetition rates.
- The speech evoked onset response (wave V and wave A) latency increased with increase in repetition rate for both the groups and this prolongation in latency was more for the older adult age group compared to the young age group. The prolongation in latency was statistically significant for all the three repetition rates.
- As the repetition rate increased the latency of speech evoked ABR sustained response (wave D and F) increased for the young group whereas the latency did not increase for the older adult age group. When the latency of sustained responses were compared across the two groups, the increase in latency for wave E and wave F was more for the older adult group compared to the young group. However, wave D of sustained complex did not show any significant difference between the two group.
- The amplitude of F0, F1 and higher harmonics (F2) decreased with increase in repetition rate for the young group and for F2 amplitude in older adult group. However when the amplitude of F0, F1 and F2 was compared across the two groups, the reduction in amplitude for F0, F1 and higher harmonics (F2) was more for the older adults compared to the young age group.

It can be seen from the above results that latency of occurrence of each wave increased significantly with increase in repetition rate for click and speech evoked ABR. This could be due to the fact that higher repetition rates causes neural fatigue and neural dysfunction due to depletion of neuro-transmitter at the hair cell-nerve junction more for the speech ABR components compared to the click evoked ABR.Thus increase in repetition rate resulted in increase in latency.

The following conclusions can be made from this study:

- The increase in latency of speech evoked ABR and click evoked ABR for the older adults suggest that the brainstem timing might be affected for the older adults. Both transient and sustained responses of speech evoked ABR shows a significant difference between the young and the older adults suggesting that both the transient and sustained responses are important while doing speech evoked ABR.
- The peripheral hearing sensitivity was intact in both the groups considered for the study, but there was a reduction in amplitude for the coding of F0, F1 and F2 for the older adult group. Reduction in coding of F0, F1 and F2 might be leading to the speech perception problems in older individuals. Although the perception of speech requires lot more component, brainstem coding of speech sounds might be one of the neural code which might be leading to the speech perception problems in older adults.

Implications of the study:

- The study can be utilised to study the subcortical coding of speech at the brainstem level in younger and the older adults.
- This knowledge could lead to objective diagnostic tests as well as techniques to determine appropriate intervention strategies and ways to monitor the effectiveness of intervention in the elderly population.
- The data obtained helps us to understand how the temporal aspect of speech and non speech sound is coded at the brainstem level.
- It highlights the necessity of further studies in different clinical populations.

References

Abel, S. M., Krever, E. M., & Alberti, P. W. (1990). Auditory detection, discrimination and speech processing in ageing, noise-sensitive and hearing-impaired listeners. *Scandinavian Audiology, 19,* 43–54.

Akhoun, I., Gallego, S., Moulin, A., Menard, M., Veuillet, E., Berger-Vachon, C., et al. (2008). The temporal relationship between speech auditory brainstem responses and the acoustic pattern of the phoneme /ba/ in normal-hearing adults. *Clinical Neurophysiology, 119,* 922–933.

Alain, C., McDonald, K. L., Ostroff, J. M., & Schneider, B. (2004). Aging: a switch from automatic to controlled processing of sounds? *Psychology and Aging, 19,* 125–133.

Allison, T., Wood, C. C., & Goff, W. R. (1983). Brain stem auditory, pattern-reversal visual, and short-latency somato- sensory evoked potentials: latencies in relation to age, sex, and brain and body size. *Clinical Neurophysiology, 55,* 619-636.

American National Standards Institute. (1991). *American National Standard Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms*. ANSI S3.1- (1991). New York: American National Standards Institute.

Anderson, S., Parbery-Clark, A., Yi, H., & Kraus, N. (2011). A neural basis of speech-in-noise perception in older adults. *Ear & Hearing, 32(3),* 1-8.

Babkoff, H., Ben-Artzi, E., & Fostick, L. (2011). Auditory temporal processes in the elderly. *Audiology Research, 1(6),* 19-21.

Babkoff, H., Muchnik, C., Ben-David, N., Furst, M., Even-Zohar, S., & Hildesheimer, M. (2002). Mapping lateralization of click trains in younger and older populations. *Hearing Research, 165,* 117–127.

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and Subcortical auditory function. *Cerebral Cortex*, *19,* 2699- 2707.

Banai, K., Nicol, T., Zecker, S. G., & Kraus, N. (2005). Brainstem Timing: Implications for Cortical Processing and Literacy. *Journal of Neuroscience*, *25(43),* 9850 –9857.

Barr, R. A., & Giambra, L. M. (1990). Age-related decrement in auditory selective attention. *Psychology and Aging*, *5,* 597–599.

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

Bergman, M. (1971). Changes in hearing with age. *Gerontologist*, *11,* 148–151.

Bess, F. H., Konkle, D. F., & Beasley, D. S. (1977). Intelligibility of time altered speech in relation to chronological aging. *Journal of Speech and Hearing Research*, *20*, 108-115.

Bidelman, G. M., & Krishnan, A. (2009). Neural correlates of consonance, dissonance, and the hierarchy of musical pitch in the human brainstem. *Journal of Neuroscience, 29,* 13165- 13171.

Boettcher, F. A., Mills, J. H., Swerdloff, J. L., & Holley, L. (1996). Auditory evoked potentials in aged gerbils: Responses elicited by noises separated by a silent gap. *Hearing Research*, *102*, 167–178.

Bonfils, P. (1989). Spontaneous otoacoustic emissions: Clinical interest. *Laryngoscope*, *99*, 752-756.

Burkard, R., & Hecox, K. E. (1983). The effect of broadband noise on the human brainstem auditory evoked response. I. Rate and intensity effects. *Journal of the Acoustical Society of America, 74,* 1204- 1213.

Burkard, R., & Hecox, K. E. (1987a). The effect of broadband noise on the human brainstem auditory evoked response. III. Anatomic locus. *Journal of the Acoustical Society of America, 81,* 1050- 1063.

Burkard, R., & Hecox, K. E. (1987b). The effect of broadband noise on the human brainstem auditory evoked response. IV. Addidivity of forward- masking and rate- induced wave V latency shifts. *Journal of the Acoustical Society of America, 81,* 1064- 1072.

Burkard, R., & Sims, D. (2001). The human auditory brainstem response to high click rates: Aging effects. *American Journal of Audiology, 10(2),* 53-61.

Carhart, R. & Jergaer, J. (1959). Preferred method of clinical determination of pure tone thresholds. *Journal of Speech and Hearing Disorders, 24,* 330- 345.

Caspary, D. M., Schatteman, T. A., & Hughes, L. F. (2005) Age-related changes in the inhibitory

response properties of dorsal cochlear nucleus output neurons: role of inhibitory inputs. *Journal of Neuroscience, 25,* 10952–10959.

Chandrasekaran, B., & Kraus, N. (2010). The scalp- recorded brainstem response to speech: Neural origins and plasticity. *Psychophysiology, 47,* 236-246.

Clinard, C. G., Tremblay, K. L., & Krishnan, A. R. (2010). Aging alters the perception and physiological representation of frequency: Evidence from human frequency-following response recordings. *Hearing Research, 264,* 48 –55.

Committee on Hearing and Bioacoustics and Biomechanics (CHABA). (1988). Speech understanding and aging. *Journal of the Acoustical Society of America, 83,* 859-895.

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,* 758–767.

Don, M., Allen, A. R., & Starr, A. (1977). Effect of click rate on the latency of auditory brain stem responses in humans. *Annals of Otology, Rhinology & Laryngology, 86,* 186-195.

Dorn, P. A., Piskorski, P., Keefe, D. H., Neely, S. T., & Gorga, M. P. (1998). On the existence of an age/threshold/frequency interaction in disortion product otoacoustic emissions. *Journal of the Acoustical Society of America, 104,* 964–971.

Dubno, J. R., Horwitz, A. R., & Ahlstrom, J. B. (2002). Benefit of modulated maskers for speech recognition by younger and older adults with normal hearing. *Journal of the Acoustical Society of America, 111,* 2897–2907.

Dubno J. R., Lee, F., Matthews, L. J., & Mills, J. H. (1997). Age-Related and Gender-Related Changes in Monaural Speech Recognition. *Journal of Speech, Language, and Hearing Research, 40,* 444–452.

Era, P., Jokela, J., Qvarnberg, Y., & Heikkinen, E. (1986). Pure-tone thresholds, speech understanding, and their correlates in samples of men of different ages. *Audiology, 25,* 338–352.

Ewertsen, H. W., & Birk-Nielson, H. B. (1971). A comparative analysis of the audiovisual, auditive and visual perception of speech. *Acta Oto-Laryngologica, 72,* 201–205.

Fitzgibbons, P. J., & Gordon-Salant, S. (1996). Auditory temporal processing in elderly listeners, *Journal of American Academy of Audiology, 7*, 183–189.

Fogerty, D., Humes, L. E., & Kewley-Port, D. (2010). Auditory temporal-order processing of vowel sequences by young and elderly listeners. *Journal of the Acoustical Society of America, 127 (4),* 2509-2520.

Fowler, C. G., & Noffsinger, D. (1983). Effects of stimulus repetition rate and frequency on the auditory brainstem response in normal cochlear-impaired, and VIII nerve/brainstem- impaired subjects. *Journal of Speech and Hearing Research, 26,* 560- 567.

Frisina, D. R., & Frisina, R. D. (1997). Speech recognition in noise and presbycusis: Relations to possible neural mechanisms. *Hearing Research, 106,* 95–104.

Frisina, R. D., & Walton, J. P. (2006). Age-related structural and functional changes in the cochlear nucleus. *Hearing Research, 216–217,* 216–223.

Gates, G. A., & Cooper, J. C. (1991). Incidence of hearing decline in the elderly. *Acta Oto-Laryngologica, 111,* 249–248.

Gates, G. A., Feeney, M. P., & Higdon, R. J. (2003). Word recognition and the articulation index in older listeners with probable age-related auditory neuropathy. *Journal of the American Academy of Audiology, 14,* 574 –581.

Geal-Dor, M., Goldstein, A., Kamenir, Y., & Babkoff, H. (2006). The effect of aging on event-related potentials and behavioral responses: comparison of tonal, phonologic and semantic targets. *Clinical Neurophysiology, 117,* 1974–1989.

Gelfand, S. A., Piper, N., & Silman, S. (1985). Consonant recognition in quiet as a function of aging among normal hearing subjects. *Journal of the Acoustical Society of America, 78(4),* 1198-206.

Gelfand, S. A., Piper, N., & Silman, S. (1986). Consonant recognition in quiet and in noise with aging among normal hearing listeners. *Journal of the Acoustical Society of America, 80,* 1589–1598.

Gonclaves, I. C., Wertzner, H. F., Samelli, A. G., & Matas, C. G. (2011). Speech and non-speech processing in children with phonological disorders: An electrophysiological study. *Clinics, 66,* 293- 298.

Gordon-Salant, S. (1987). Age-related differences in speech recognition performance as a function of test format and paradigm. *Ear & Hearing, 8,* 270–27.

Gordon-Salant, S., Fitzgibbons, P. J. (1999). Profile of auditory temporal processing in older listeners. *Journal of Speech Language and Hearing Research, 42,* 300-311.

Gordon-Salant, S., Pearson, J. D., Morrell, C. H., Brant, L. J., Metter, E. J., Klein, L. L, etal. (1995). Gender differences in a longitudinal study of age-associated hearing loss. *Journal of the Acoustical Society of America, 97,* 1196–1205.

Green, D. M. (1984). Temporal factors in psychoacoustics. In A. Michelsen (Ed.), Time resolution in auditory systems (pp. 128-140). Berlin: Springer-Verlag.

Greenberg, S., Marsh, J. T., Brown, W. S., & Smith, J. C. (1987). Neural temporal coding of low pitch. I. Human frequency- following responses to complex tones. Hearing Research, 25, 91- 114.

Grose, J. H., Hall, J. W., & Buss, E. (2006). Temporal processing deficits in the pre-senescent auditory system. *Journal of the Acoustical Society of America, 119,* 2305-2315.

Hall, J.W. (1992). *Handbook of Auditory Evoked Responses*. Boston: Allyn & Bacon.

Hayes, D. (2003). Screening methods: Current status. *Mental Retardation & Developmental Disability Research Revised, 9,* 65-72.

Helfer, K., & Vargo, M. (2006). Speech Recognition and Temporal Processing in Middle-Aged Women. *Journal of the American Academy of Audiology, 20(4),* 264–271.

Hirsh, I. J. (1959). Auditory perception of temporal order. *Journal of the Acoustical Society of America, 31,* 759–767.

Hoormann, J., Falkenstein, M., Hohnsbein, J., & Blanke, L. (1992). The human frequency-following response (FFR): Normal variability and relation to the click-evoked brainstem response. *Hearing Research, 59,* 179–188.

Hornickel, J., Anderson, S., Skoe, E., Yi, E., & Kraus, N. (2011). Subcortical representation of speech fine structure relates to reading ability. *Neuro Report, 23,* 6–9.

Hornickel, J., Skoe, E., & Kraus, N. (2009). Subcortical laterality of speech encoding. *Audiology and Neurotology, 14,* 198–207.

Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Subcortical differentiation of voiced stop consonants: relationships to reading and speech in noise perception. *Proceedings of the National Academy of Science, 106,* 13022- 13027.

Hull, R. H. (1989). *Hearing evaluation in the elderly.* In R. H. Hull & K. M. Griffin (Eds.), Communication disorders in aging (pp. 426–440). Beverly Hills, CA: Sage.

Humes, L. E. (1996). Speech understanding in the elderly. *Journal of the American Academy of Audiology, 7,* 161–167.

Hutchinson, K. M., Alessio, H. M., & Baiduc, R. R. (2010). Association between cardiovascular health and hearing function: Pure-tone and distortion product otoacoustic emission measures. *American Journal of Audiology, 19,* 26-35.

Hyde, M. L. (1985). *The effect of cochlear lesions on the ABR*. In: J.T. Jacobson (Eds.), The Auditory Brainstem Response, College-Hill Press, San Diego.

Jacobson, J. T., Murray, T. J., & Deppe, U. (1987). The effects of ABR stimulus repetition rate in multiple sclerosis. *Ear & Hearing, 8,* 115–120.

Jewett, D. L., Romano, M. N., & Williston, J. S. (1970). Human auditory evoked potentials: Possible brain stem components detected on the scalp. *Science, 167,* 1517–1518.

Johnson K. L., Nicol, T., Zecker, S., & Kraus, N. (2008). Developmental Plasticity in the Human Auditory Brainstem. *Journal of Neuroscience, 28(15),* 4000-4007.

Khaladkar, A. A., Kartik, N., & Vanaja, C. S. (2005). *Speech Burst and Click Evoked ABR*. Poster presented at 36th ISHACON, Mysore.

Kim, S., Frisina, R. D., Mapes, F. M., Hickman, E. D., & Frisina, D. R. (2006). Effects of age on binaural speech intelligibility in normal hearing adults. *Speech Communication, 48,* 591–597.

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

Klatt, D. (1980). Software for cascade / parallel formant synthesizer. *Journal of the Acoustical Society of America, 67,* 971- 975.

Klein, B. E., Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, R., Mares-Perlman, J. A. etal. (1998). Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin. The Epidemiology of Hearing Loss Study. *American Journal of Epidemiology, 148(9),* 879–86.

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

Krizman, J., Skoe, E., & Kraus, N. (2010). Stimulus Rate and Subcortical Auditory Processing of Speech. *Audiology Neurotolgy, 15,* 332-342.

Lasky, R. E. (1984). A developmental study on the effect of stimulus arte on the auditory brainstem response. *Electroencephalography and Clinical Neurophysiology, 59,* 411-419.

Lasky, R. E. (1997). Rate and adaptation effects on the auditory evoked brainstem response in human newborn and adults. *Hearing Research, 111,* 165- 176.

Lee, K. M., Skoe, E., Kraus, N., & Ashley, R. (2009). Selective subcortical enhancement of musical intervals in musicians. *Journal of Neuroscience, 29,* 5832–5840.

Lonsbury-Martin, B. L., Cutler, W. M. & Martin, G. K. (1991). Evidence for the influence of aging on distortion-product otoacoustic emissions in humans. *Journal of the Acoustical Society of America, 89(4),* 1749-1759.

Mamatha, N. M. & Barman, A. (2008). Effect of repetition rate on auditory brainstem response in adults and elderly. *Articles based on dissertation at A.I.I.S.H, 1,* 39-51.

Marsh, J. T., Brown, W. S., & Smith, J. C. (1974). Differential brainstem pathways for the conduction of auditory frequency following responses. *Electroencephalography and Clinical Neurophysiology, 38,* 415- 422.

Mazelova, J., Popelar, J. & Syka, J. (2003). Auditory function in presbycusis: peripheral vs. central changes. *Experimental Gerontology, 38,* 87–94.

Mehta, G., & Singh, N. K. (2012). *Stimulus rate and subcortical auditory processing of speech in children with learning disability*. Poster presented at 44th ISHACON, Hyderabad.

Mills, J. H., Schmeidt, R. A., & Schulte, B. A., & Dubno, J. R. (2006). Age-related hearing loss: A loss of voltage, not hair cells. *Seminars in Hearing, 27,* 228 –236.

Moser, T., Neef, A., & Khimich, D. (2006). Mechanisms underlying the temporal precision of sound coding at the inner hair cell ribbon synapse. *Journal of Physiology, 576 (1),* 55–62.

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences of the United States of America, 104,* 15894–15898.

Musacchia, G., Strait, D., & Kraus, N. (2008). Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and non-musicians. *Hearing Research, 241,* 34–42.

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

Nabelek, A. K., & Robinson, P. K. (1982). Monaural and binaural speech perception in reverberation for listeners of various ages. *Journal of the Acoustical Society of America, 71,* 1242–1248.

Ostroff, J. M., McDonald, K. L., Schneider, B. A., & Alain, C. (2003). Aging and the processing of sound duration in human auditory cortex. *Hearing Research, 181*, 1–7.

Parbery-Clark, A., Skoe, E., & Kraus, N. (2009). Musical experience limits the degradative effects of background noise on the neural processing of sound. *Journal of Neuroscince, 29,* 14100–14107.

Patterson, J. V., Michalewski, H. J., Thompson, L. W., Bowmanm, T. E., & Litzelman, D. K. (1981). Age and Sex Differences in the Human Auditory Brainstem Response. *Journal of Gerontology, 36(4),* 455-462.

Pichora-Fuller, M. K. (2003). Coognitive aging and auditory information processing. *International Journal of Audiology, 42 (Suppl 2),* 2S26- 2S32.

Pichora-Fuller, M. K., Schneider, B. A., & Mcdonald, E., et al. (2007). Temporal jitter disrupts speech intelligibility: A simulation of auditory aging. *Hearing Research, 223,* 114 –121.

Pichora-Fuller, M. K., & Souza, P. E. (2003). Effects of aging on auditory processing of speech. *International Journal of Audiology, 42, Supplement 22S,* 11–16.

Plomp, R., & Mimpen, A. M. (1979). Speech-reception threshold for sentences as a function of age and noise level. *Journal of the Acoustical Society of America, 66,* 1333–1342.

Plyler, P. N., & Ananthanarayan, A. K. (2001). Human frequency-following responses: Representation of second formant transitions in normal-hearing and hearing impaired listeners. *Journal of the American Academy of Audiology, 12,* 523–533.

Pratt, H., & Sohmer, H. (1976) Intensity and rate functions of cochlea and brainstem evoked responses to click stimuli in man. *Archives of Otorhinolaryngology, 212,* 85-93.

Prieve, B. A., & Falter, S. R. (1995). COAEs and SSOAEs in adults with increased age. *Ear & Hearing, 16,* 521–528.

Ranjan, R. (2011). Effect of stimulus rate on Subcortical auditory processing in children. Unpublished dissertation done at A.I.I.S.H, Mysore.

Robinson, D. W., & Sutton, G. (1978). *A comparative analysis of data on the relation of pure-tone audiometric thresholds to age.* NPL report Ae84. National Physical Laboratory, Teddington.

Rosenhamer, H. J., Lindstrom, B., & Lundborg, T. (1980). On the use of click-evoked electric brainstem responses in audiological diagnosis. II. The influence of sex and age upon the normal response. *Scandinavian Audiology, 9(2),* 93-100.

Ross, B., Fujioka, T., Tremblay, K. L., & Picton, T. W. (2007). Aging in binaural hearing begins in mid-life: evidence from cortical auditory-evoked responses to changes in interaural phase. *Journal of Neuroscience, 27,* 11172–11178.

Rowe, M. J., III (1978). Normal variability of the brain-stem auditory evoked response in young and old adult subjects. *Electroencephalography and Clinical Neurophysiology, 44,* 459-470.

Russo, N. M., Nicol, T., Musacchia, G., & Kraus, N. (2004). Brainstem responses to speech syllables. *Clinical Neurophysiology, 115 (9),* 2021–2030.

Russo, N., Nicol, T., Trommer, B., Zecker, S., & Kraus, N. (2009). Brainstem transcription of speech is disrupted in children with autism spectrum disorders. *Developmental Science, 12,* 557- 567.

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

Russo, N. M., Skoe, E., Trommer, B., Nicol, T., Zecker, S., & Bradlow, A. (2008). Deficient brainstem encoding of pitch in children with Autism Spectrum Disorders. *Clinical Neurophysiology, 119,* 1720-1731.

Schneider, B. A., Daneman, M., & Pichora-Fuller, M. K. (2002). Listening in aging adults: From discourse comprehension to psychoacoustics. *Canadian Journal of Experimental Psychology, 56,* 139–152.

Schneider, B. A., & Hamstra, S. J. (1999). Gap detection thresholds as a function of tonal duration for younger and older listeners. *Journal of the Acoustical Society of America, 106,* 371–380.

Schneider, B. A., & Pichora-Fuller, M. K. (2001). Age-related changes in temporal processing: implications for speech perception. *Seminars in Hearing, 22,* 227– 39.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), Handbook of aging and cognition (pp. 155–220). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Schwartz, D. M. & Berry, G. A. (1985). *Normative aspects of the ABR.* In: J.T. Jacobson (Eds.), The Auditory Brainstem Response, College-Hill Press, San Diego.

Shuknecht, H. F. (1964). Further observations of the pathology of presbycusis. *Archives of Otolaryngology, 80,* 369–382.

Shuknecht, H. F. (1974). Pathology of the ear. Cambridge, MA: Harvard University Press.

Shuknecht, H. F. (1955). Presbycusis. *Laryngoscope, 65,* 402–419.

Sinha, S. K., & Basavaraj, V. (2010a). Lateral Asymmetry in Speech Processing at the Brainstem: Evidence from Speech Evoked ABR. *Journal of All India Institute of Speech and Hearing, 29 (1).* 101- 109.

Sinha, S. K. & Basavaraj, V. (2010b). Speech evoked auditory brainstem responses : a new tool to study brainstem encoding of speech sounds. *Indian Journal of Otolaryngology Head & Neck Surgery, 62,* 395- 399.

Skoe, E., & Kraus, N. (2009). *The Effects of Musical Training on Sucortical Processing of a Missing Fundamental Piano Melody.* IL: Society of Neuroscience, Chicago.

Smith, J.C., Marsh, J. T., & Brown, W. S. (1975). Far- field recorded frequency- following responses: Evidence for the locus of brainstem sources. *Electroencephalography and Clinical Neurophysiology, 39,* 465- 472.

Stoll, W., Hustert, B., & Nieschalk, M. (1998). Distortion product Otoacoustic Emissions in Middle- aged subjects with Normal versus potentially presbycusis high frequency hearing loss, *Audiology, 37,* 83- 99.

Strait, D. L., Skoe, E., Kraus, N., & Ashley, R. (2009). Musical experience and neural efficiency: effects of training on subcortical processing of vocal expressions of emotion. *European Journal of Neuroscience, 29,* 661–668.

Strouse, A., Ashmead, D. H., Ohde, R. N., & Grantham, D. W. (1998). Temporal processing in the aging auditory system. *Journal of the Acoustical Society of America, 104,* 2385–2399.

Sumesh, K., & Barman, A. (2010). Brainstem responses to speech in normal hearing and cochlear hearing loss individuals. *Articles based on dissertation at A.I.I.S.H, V,* 185-199.

Thornton, A. R. D., & Coleman, M. J. (1975). The adaptation of cochlear and brainstem auditory evoked potentials in humans. *Electroencephalography and Clinical Neurophysiology, 39,* 399- 406.

Tremblay, K. L., Billings, C. J., Friesen, L. M., & Souza, P. E. (2003). Neural representation of amplified speech. *Ear and Hearing, 15*, 92-102.

Trune, D. R., Mitchell, C., & Phillips, D. S. (1987). The relative importance of head size, gender and age on the auditory brainstem response. *Hearing Research, 32,* 165-174.

Vander, W., Kathy, R., Burns, & Kristen, S. (2011). Brainstem responses to speech in younger and older adults. *Ear & Hearing, 32(2),* 168-180.

Vaughan, N. E., & Letowski, T. (1997). Effects of age, speech rate, and type of test on temporal auditory processing. *Journal of Speech Language and Hearing Research, 40,* 1192-1200.

Warrier, C. M., Johnson, K. L., Hayes, E., Nicol, T., & Kraus, N. (2004). Learning impaired children exhibit timing deficits and training- related improvements in auditory cortical responses to speech in noise. *Experimental Brain Research, 157,* 431- 441.

Wible, B., Nicol, T., & Kraus, N. (2004). Atypical brainstem representation of onset and formant structure of speech sounds in children with language based learning problems. *Biological Psychology, 67*, 299–317.

Wible, B., Nicol, T., & Kraus, N. (2005). Correlation between brainstem and cortical auditory processes in normal and language- impaired children. *Brain, 128,* 417- 423.

Wiley, T. L., Cruickshanks, K. J., Nondahl, D. M., Tweed, T. S., Klein, R., & Klein, B. E. K. (1998). Aging and word recognition in competing message. *Journal of the American Academy of Audiology, 9,* 191–198.

Wingfield, A., McCoy, S. L., Peelle, J. E., Tun, P. A., & Cox, L. C. (2006). Effects of adult aging and hearing loss on comprehension of rapid speech varying in syntactic complexity. *Journal of the American Academy of Audiology, 17,* 487–497.

Wong, P. C., Skoe, E., Russo, N. M., Dees, T., & Kraus, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience, 10(4),* 420–422.

Worden, F. G., & Marsh, J. T. (1968). Frequency-following (microphonic-like) neural responses evoked by sound. *Electroencephalography and Clinical Neurophysiology, 25, 42-52.*

Yagi, T., & Kaga, K. (1979). The effect of the click repetition rate on the latency of the auditory evoked brainstem response and its clinical use for a neurological diagnosis. *Archieves of Otorhinolaryngology, 222,* 91- 97.