EFFECT OF STIMULUS RATE ON SUBCORTICAL AUDITORY PROCESSING IN CHILDREN

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Dedicated to

My Dear ...

Father & Mother

Family Members

&

Animesh Sir

Who taught me the Real meaning of Life.....

CERTIFICATE

This is to certify that this dissertation entitled ***"Effect of stimulus rate on subcortical auditory processing in children"*** is the bonafide work submitted in part fulfillment for the Degree of Master of Science (Audiology) of the student with Registration No. : 09AUD027. 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.

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June, 2011

CERTIFICATE

This is to certify that the dissertation entitled ***"Effect of stimulus rate on subcortical auditory processing in children"*** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier in any other University for the award of any Diploma or Degree.

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DECLARATION

This is to certify that this Master's dissertation entitled ***"Effect of stimulus rate on subcortical auditory processing in children"*** is the result of my own study under the guidance of Dr. Animesh Barman, Reader in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted in any other University for the award of any Diploma or Degree.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter-1

Introduction

The neural encoding of sound stimulus begins at auditory nerve and continues till the cortex via auditory brainstem. Brainstem responses to simple stimuli are well defined and used widely in the clinical practice in the evaluation of the auditory pathway integrity (Moller, 1999; Starr & Don, 1988). The role of brainstem in processing a complex signal varying in many acoustic dimension continuously over time, such as a speech syllable have recently become popular among audiologist as it can be easily recorded with the help of conventional auditory techniques. The ABR is ideally suited for evaluating difficult to test patients because it passively elicit neurophysiological response to auditory stimuli and does not require the patient to actively attend or respond to the stimulus.

The click-evoked ABR is used widely by clinicians to evaluate hearing and the integrity of the auditory brainstem in certain populations, such as infants or neurologically impaired patients (Starr & Don, 1988). Speech syllable are being used to record evoked potential as it has got the potential to understand neural processing of speech stimuli. ABRs recorded to speech reflect the acoustics with such accuracy that when the evoked response is played back as an auditory stimulus, it is perceived as intelligible speech (Galbraith et al., 1995). Auditory brainstem response provides direct information about how the complex stimuli like speech is encoded at the auditory system. According to Banai (2007), Johnson (2005); Kraus and Nicol (2005), separate neural mechanisms are responsible for processing different aspects of speech sound. Speech sounds consists of mainly three components. The fundamental frequency which provides information about the source, the formants which are filter characteristics conveyed by the selective enhancement or attenuation of the harmonics and the timing information of the major acoustics landmarks. The neural processing of all these information can easily be capture by using speech stimulus to elicit auditory potential. Brainstem responses to a speech syllable can be divided into two parts- transient and sustained response. The onset responses are transient, akin to the well-documented clinical measure that use click or tonal stimuli as a tool for assessing both peripheral hearing and retrocochlear pathology lesions such as tumors of the auditory nerve or brainstem (Hall, 1992).

Brainstem neurons phase lock to the temporal structure of the eliciting sound, giving rise to a sustained response known as the frequency- following response (FFR), which reflects the encoding of the periodic (i.e. frequency-specific) information of the stimulus > 2kHz (Moushegian, Rupert & Stillman, 1973; Hoormann, Falkenstein, Hohnsbein & Blanke., 1992). The transient (e.g. click-ABR) and sustained ABRs are assumed to originate from separate neural generators (Chandrasekaran & Kraus, 2010). To represent the transient features of speech sounds, the auditory brainstem represents steady state and time-varying formant information, by phase locking to the fundamental frequency (FO) and formant related harmonics of the stimulus. Subcortical synchrony is observed in response to synthesized and natural English vowels (Krishnan, 2002; Dajani, Purcell, Willy, Kunov & Picton, 2005; Aiken & picton, 2008) consonant-vowel formant transitions (Plyler & Ananthanarayan, 2001; Russo, Nicol, Musacchia & Kraus., 2004; Akhoun, et al., 2008; Banai et al., 2009), speech syllables (Hornickel, Skoe, Nicol, Zecker & Kraus, 2009), and words (Galbraith, et al., 2004). The evoked brainstem potential in response to a stop consonant speech syllable such as /da/ consists of a transient response similar to the click-

ABR (Song, Banai, Russo & Kraus, 2006) reflecting the transient stop burst of the consonant /d/ and an FFR to the voiced formant transition from the /d/ to the vowel /a/. Stop consonants are especially vulnerable to misperception in clinical populations, including poor readers (de Gelder & Vroomen, 1998; Tallal, 1981), people with hearing loss (Townsend & Schwartz, 1981; Van Tasell, Hagen, Koblas & Penner, 1982) and people with auditory processing disorders (Banai & Kraus, 2008; Bellis, 2002)

The fidelity of subcortical encoding of speech sounds, as measured using auditory evoked potentials, could be interpreted as reflecting automatic detection of the acoustic features of sound in the absence of activity- dependent changes usually associated with higher processing structures, such as the cortex. Greenberg (1980) was first to adopt complex stimuli such as the vowel formants to record ABR. His results were similar with study done by Young and Sachs (1979), Greenberg, young and Sachs believed that the speech patterns were preserved in the discharge patterns of the auditory nerve and these encoded patterns in the auditory nerve were further transmitted to the brainstem and the higher auditory structures. The results suggests that auditory brainstem responses to speech mimics the acoustic characteristics of the signal with remarkable fidelity, thereby helping one to understand and derive theoretical and clinical applications relevant to the auditory processing. FFR has been used to study the brainstem coding deficits in several communication disorders such as children with learning problems and adults with cochlear hearing loss. Some children with language-based learning problems exhibit abnormal neural encoding of the spectral and temporal information crucial for accurate perception of sounds (King, Warrier, & Hayes, 2001; Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001). Some also experience abnormal susceptibility to the demands placed on the auditory system by rapidly presented temporal information (Wible, Nicol, & Kraus, 2002; Nagarajan, Mahncke, Salz, Tallal, Roberts, & Merzenich, 1999). Electrophysiological studies can provide information about the sequence, timing and location of neural activity and therefore provide an objective analytic window to evaluate temporal processing in the auditory system (Basu, Krishnan & Fox, 2010).

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 temporal phenomena present in acoustic stimuli manifest themselves in different ways depending on the task (Green, 1984) and 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.

NEED FOR THE STUDY:

- Early studies of the ABR used simple stimuli such as clicks and sinusoidal tones to tap into and maximize these transient and sustained ABRs. Although clicks and tones have been instrumental in defining these basic response patterns, they are poor approximations of the behaviorally relevant sounds that we encounter outside the laboratory (e.g., speech and music, non-speech vocal sounds, and environmental sounds). Therefore there is a need to study the processing of speech sound at the brainstem level.

- In children it is difficult to get the behavioral responses. Speech evoked ABR is an electrophysiological test which does not require the co-operations from the client and gives the information about brainstem encoding of speech sounds. Speech evoked ABR has been found very useful in the diagnosis of children with learning disability (Johnson, 2005; Kraus & Nicol 2005; Banai, 2007).
- The processing of speech and speech sounds is potentially more “meaningful” with respect to psychological and linguistic issues, than the processing of clicks. 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 children.
- 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.
- Temporal processing that utilized brainstem auditory evoked responses by Cunningham, Nicol, Zecker, Bradlow and Kraus, (2001); King, Warrier, Hayes, and Kraus, (2002); Wible, Nicol and Kraus, (2004) done in children with specific language impairment age from 4 to 11 years in 10 children and age matched control group was taken to compare data. However subject in the control group was not

categorized into different groups to observe developmental changes. Thus, there is need to study how temporal processing is limited during developmental changes in normal hearing children.

Aim of the study:

- To investigate the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on speech and click-evoked ABR and FFR in children.
- To develop a data base for how the non-speech stimulus and speech stimulus coded at brainstem during early developmental period.

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 auditory brainstem response 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, the effects of neural fatigue and desynchronization become increasingly evident, helping to reveal minute differences in how temporal cues are processed in various populations.

Brainstem responses to Non-speech stimulus:

Auditory brainstem response (ABR) is widely used in audiology and neurotology as an objective tool for assessing hearing sensitivity and auditory nerve function. The ABR represents the initial processing and transmission of acoustical signals through the auditory nerve and brainstem (Moller, 1994). Brief acoustic signals, such as clicks, tone bursts and tone pips have been used to elicit the ABR. The ABR is a measure of neural integrity, has been shown to be extraordinarily useful as a screening tool for hearing loss and other auditory system abnormalities, and as a screening tool to identify retrocochlear disorders, such as acoustic neuroma.

The ABR is ideally suited for evaluating difficult to test patients because it is a passively elicited neurophysiological response to auditory stimuli and does not require the patient to actively attend or respond to the stimulus. The click-evoked ABR is used widely by clinicians when evaluating hearing and the integrity of the auditory brainstem in certain populations, such as infants or neurologically impaired patients (Starr & Don, 1988). The auditory brainstem response (ABR) is generated by synchronous firing of structures along the ascending auditory pathway, which include the auditory nerve, cochlear nuclei, superior olivary nuclei, lateral lemniscus, and inferior colliculus (Moller & Jannetta, 1985). Stimulus rates above approximately 30 stimuli per second, the latency of all components of the ABR increases and amplitude of the later components decreases (Don et al., 1977). Latency does not increase by the same amount for all components. The later waves of the ABR show a greater latency increase than the earlier waves, which results in prolongation of the interwave interval of waves I-V. The different effect of rate on various components of the ABR suggests the presence of peripheral and central rate effects. More rapid stimulus rates also tend to reduce the clarity and reproducibility of responses, particularly for the later components. Comparison of ABRs obtained at high rates to those obtained at slower presentation rates is sometime used to evaluate suspected neurological lesions (Don et al., 1977). Mamatha & Barman (2008) reported that shift in latency and decreased amplitude for higher repetition rates and this effect was greater at lower intensity and in older age group. The approximate latency shift of wave V can be 0.5 ms to 0.6 ms in normals and 0.6 ms to 0.8 ms in subjects with SNHL when rate was increased from 11.1/sec to 90.1/sec. Ackley et al. (2006) determine the degree of wave V latency shift with rapid stimulus repetition rate in normal subjects at three different repetition rates (61.1/sec, 45.1 or 31.1/sec). Results suggest that this shift was found to be slightly and predictably greater for the 61.1/sec rate than for rates of 45.1 or 31.1/sec. Using the 61.1/sec rate diagnostically seems to make the test more sensitive to subtle auditory neurological lesions, including acoustic nerve tumors of 1.0 cm size and smaller. Therefore, a wave V latency of >6.25 msec (5.89 msec + 2 SDs) may be diagnostically sensitive to subtle neurological lesions with a 61/sec stimulus repetition rate. Burkard and Hecox (1983) also described decreasing amplitude, increasing wave V latency, and prolonged I-V interpeak latency with increase in repetition rate. Burkard and Sims (2004) showed that latency increase was nearly linear with stimulus rate increases between 25 and 75 stimuli per second and was non-linear with rates exceeding 75/sec.

Brainstem responses to Speech Syllables

The electrophysiological brainstem response to a speech sound is a complex waveform and has been mostly elicited using /da/ stimulus. Various stimuli have been used to evoke speech ABR and the list of stimuli used to evoke speech evoked ABR extends beyond speech syllables and includes words and phrases (e.g., “car,”“minute,” “chair,” “rose” (Galbraith et al., 1995), and “dani” (Wang et al., 2010). Several researchers have also started to explore the use of environmental sounds, affective non speech vocal sounds (e.g., a baby’s cry; Strait et al., 2009) and musical sounds as viable stimuli for brain stem-evoked recordings. Work on music-evoked ABRs has included a bowed cello note (Musacchia et al., 2007, 2008), a five-note musical melody (Skoe & Kraus 2009), as well as consonant and dissonant two-note intervals synthesized from an electric piano (Lee et al., 2009) and tone complexes (Greenberg et al., 1987; Bidelman & Krishnan 2009).

Speech evoked ABR waveform to a syllable /da/ comprises of onset response and sustained peaks which is also known as frequency following responses (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 (onset burst). The sustained FFR is synchronized to the periodicity (repeating aspects) 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 the wave V elicited by click stimuli, followed immediately by a negative trough (wave A). In most subjects, positive peaks corresponding to click-evoked auditory brainstem response waves I and III are also visible. The fundamental frequency occurs at approximately 15 msec, 24 msec and 33 msec in stimulus corresponding to wave D (22) msec, E (31) msec and F (40 msec) 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 offset of 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 et al., 1974; Smith et al., 1975). A representative sample of the waveform and the stimulus has been given below:

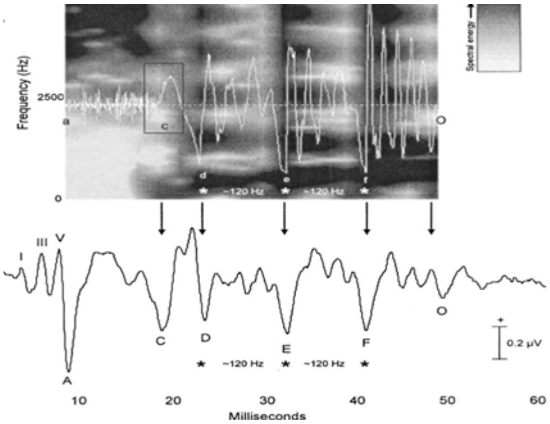

Figure 2.1. /da/ stimulus and its response at the brainstem (sustained and transient response). The stimulus waveform has been shifted 7 msec to compensate for neural lag in the response.

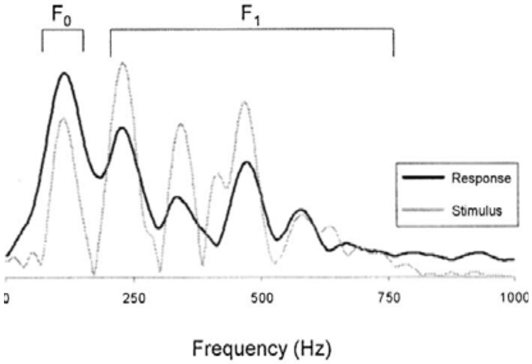

Figure 2.2. Fourier analysis of the stimulus (light line; filtered at 400 Hz to mimic the low-pass characteristics of the midbrain) and the brain stem response (dark line, time range of 23 to 44 msec).

The brain stem response demonstrates remarkable fidelity to the stimulus in the frequency domain for both F0 and F1. Although FFR, like the cochlear microphonics, accurately reproduce the input stimulus, there are clear differences between the two potentials. FFR is a neural response rather than the preneural responses. The onset of the FFR shows a delay of 5-10 msec even for simple sinusoidal signal suggesting a site of origin rostral to the cochlea (Worden & Marsh, 1968). The FFRs may be confused with the stimulus artifact as well, but the latency of a stimulus related artifact is around 0.029 msec for an average ear canal length of 2.7 cm whereas the average latency of FFR is around 5-10 msec. Also, the FFR demonstrates small but appreciable amplitude and phase fluctuations that suggest that the responses are not a perfect replica of the input signal (Worden & Marsh, 1968).

There is a close relationship between the pattern of the acoustic stimulus and the FFR temporal structure. Akhoun et al., (2008) reported that frequency following response (FFR) waveform mimicked the 500 Hz low pass filtered temporal waveform of phoneme /ba/ with a latency shift of 14.6 ms. In addition, the onset response and FFR latencies decreased with increasing stimulus intensity, with a greater rate for FFR (1.4 ms/10 dB) than for onset response (0.6 ms/10 dB). It was concluded that the results provide further insight into the temporal encoding of basic speech stimulus at the brainstem level in humans.

Brainstem responses to Speech syllables in sensorineural hearing loss

Both the transient responses as well as the frequency following responses are affected by sensorineural hearing impairment. It has been reported in literature that the coding of the second formant transition is affected in sensorineural hearing impaired individuals. Pyler and Ananthanarayan (2001) reported that the FFR did encode the second formant transition in normal hearing listeners. However, individuals with sensorineural hearing impairment suggested degradation in the encoding of the second formant transition. The 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 (i.e. wave V) is also affected in individuals with sensorineural hearing impairment. Khladakar, Kartik and Vanaja (2005) observed that the ABR wave V latency for the click stimulus was within normal limits, whereas speech burst evoked ABRs showed deviant results in individuals with sensorineural hearing impairment, suggesting that speech evoked ABR offers an opportunity to isolate normal speech processing from abnormal speech processing.

Further, as the degree of sensorineural hearing impairment increases the coding of speech parameters are more affected at the brainstem. Sumesh & Barman (2010) explored the relationship between the cochlear hearing loss and the brainstem encoding of 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 parameters). Further, they also noticed that the transient and frequency following responses were more affected with the increased in severity of hearing loss. The authors attributed this finding to difficulty in coding temporal fine structure by the cochlear hearing loss group. Sumitha and Barman (2010) investigated the cortical neural processing for spectrally different speech sound (ba, da & ga) in individuals with cochlear hearing loss. The latencies were shorter in the normal population and prolonged in clinical population. Amplitude did not show any difference in the normal population and clinical population.

Brainstem responses to Speech syllables in learning impaired children

There has been significant research in the 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 distinguishes them from the larger Learning problem population (Banai et al., 2005; Cunningham et al., 2001; Hayes et al., 2003; King et al., 2002; Russo et al., 2005; Wible et al., 2004, 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 deficit in cortical processing is associated with the delay in auditory brainstem responses of the learning impaired children. King et al., (2002) recorded auditory brainstem responses in normal children and children clinically 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 differences between normal and learning impaired population. Deficits in cortical processing of signals in noise were seen for learning disabled subjects with delayed brainstem responses to /da/, but not for learning disabled children with normal brainstem measures. In addition, children with delayed onset responses to a speech stimulus also have delays in the 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 the brainstem appear to have a deleterious effect on cortical responses to the same stimulus.

Wible, Nicol and Kraus (2004) investigated how the human auditory brainstem represents elements of speech sounds differently in children with language-based learning problems, especially under stress of rapid stimulation. In response to the onset of the speech sound /da/, wave V–A of the auditory brainstem response (ABR) had a significantly shallower slope 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 higher-level language processes.

Brainstem responses to speech syllables in children with autism spectrum disorder

Russo et al., (2008) investigated the subcortical representations of prosodic speech in children with autism spectrum disorder. They recorded brainstem responses to speech syllable /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 the latency or the amplitude of the ABR evoked by the click stimulus. Thus, the researcher concluded that speech evoked ABR may have clinical implications for diagnostic and remediation strategies in a subset of children with autism spectrum disorder.

Russo, Nicol, Trommer, Zecker and Kraus (2009) measured brainstem responses to the syllable /da/, in quiet and background noise in children with autism spectrum disorder who had normal intelligence and hearing. Children with autism spectrum disorder exhibited deficits in both the transient responses (i.e wave V & wave A) and sustained responses (frequency following responses) despite normal click-evoked brainstem responses. Children with autism 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 the children with autism spectrum disorder.

Brainstem responses to Speech syllables in poor readers and good readers

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 awareness and speech-in-noise perception depend on reciprocal interactions 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 compared to the good readers. The authors suggested that the reading skill may depend on the integrity of subcortical auditory mechanisms and are consistent with the idea that subcortical representation of the acoustic features of speech may play a role in normal reading as well as in the development of reading disorders.

Speech ABR response to auditory training

It is noteworthy that Learning problem children with abnormal brain stem timing of peaks A and C are most likely to show both physiological and behavioral improvements after auditory training with commercially available software (Hayes et al., 2003; King et al., 2002; Russo et al., 2005). Thus, the brain stem 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 brain stem response itself, Training-related changes have been observed 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 brain stem neural activity less susceptible to the detrimental effects of background noise.

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

Temporal Processing studies using Click evoked ABR & Speech evoked ABR

Several authors have utilized speech ABR to study the temporal processing of speech in normal hearing individuals as well as in children with specific language impairment.

Papakonstantinou et al., (2011) investigated behavioural and objective measures of temporal auditory processing and their relation to the ability to understand speech in noise. The experiments were carried out on a homogeneous group of seven hearing-impaired listeners with normal sensitivity at low frequencies (up to 1 kHz) and steeply sloping hearing losses above 1 kHz and for comparison, data were also collected for five normal-hearing listeners. Results suggest that the wave-V thresholds indicated a relation to SRTs and the ability to process temporal fine structure.

Papakonstantinou et al., (2011); 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-evoked onset responses likely reflect acoustic differences. The frequency-following response (FFR) was also rate dependent, with response magnitude of the higher frequencies (>400 Hz), but not the frequencies corresponding to the 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 mechanisms for high- versus low-frequency components of the response.

Basu, Krishnan and Fox (2010) also investigated in children with Specific language impairment showed abnormalities at the brainstem level, consistent with a temporal processing deficit by using the sustained frequency following response (FFR) and the onset auditory brainstem responses (ABR). The neural encoding of tonal sweeps, as reflected in the FFR, for different rates of frequency change, and the effects of reducing inter-stimulus interval on the ABR components were evaluated in 10 children with Specific language impairment and 10 children with normal language development. Authors found that the Specific language impairment group showed degraded FFR phase-locked neural activity that failed to faithfully track the frequency change presented in the tonal sweeps, particularly at the faster sweep rates. Specific language impairment children also showed longer latencies for waves III and V of the ABR and a greater prolongation of wave III at high stimulus rates (>30/sec), suggesting greater susceptibility to neural adaptation. These results suggest that a disruption in the temporal pattern of phase-locked neural activity necessary to encode rapid frequency change and an increased susceptibility to desynchronizing factors related to faster rates of stimulus presentation in children with Specific language impairment.

Thus, the review of literature suggests that there was a need to study in normal population that how temporal processing is limited which utilizes brainstem responses and the present study was taken up with the aim of investigating the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on speech and click-evoked ABR and FFR in children.

Chapter-3

Method

The present study was taken up with the aim of investigating the interactions between auditory temporal processing and stimulus complexity by examining the effects of stimulus rate on speech and click-evoked ABR and FFR in children. To accomplish the aim follow method was adopted.

Subjects:

A total of fifty seven (57) subjects participated in the study. Subject's age between 5 to 10 years were selected. All the participants were then divided into the follows five groups, based on their age:

Group I: 5years to 5 years 11 months, (10 children)

Group II: 6 years to 6 years 11 months, (11 children)

Group III: 7 years to 7 years 11 months, (13 children)

Group IV: 8 years to 8 years 11 months, (13 children)

Group V: 9 years to 9 years 11 months, (10 children)

These groups were made to observe the development of auditory temporal processing change.

Subject selection criteria:

The subjects were selected based on the following criteria:

- The behavioral thresholds were within 15 dB HL at all frequencies from 250 Hz to 8 KHz and 250 Hz to 4 KHz for air conduction and Bone conduction respectively in both ears.
- All had “A” type tympanograms with normal acoustic reflex thresholds in both ears.
- All of them passed the screening checklist for auditory processing (SCAP) developed by Yathiraj and Mascarenhas (2004) indicating absent auditory processing disorder.
- None of them reported to have any history of neurological or otological problems.
- No illness on the day of testing was reported by the subjects.
- They did have Normal click evoked-ABR at lower (11.1/sec) and higher (90.1/sec) repetition rate, indicating absent of retrocochlear pathology (RCP).

Instrumentation:

- A calibrated diagnostic audiometer, (GSI-61) with TDH-50P earphones was used to obtain air conduction thresholds. Radio ear B-71 bone vibrator was used for bone conduction testing.
- A calibrated middle ear analyzer, (GSI tympstar) was used to record tympanogram and acoustic reflexes measurements.
- Auditory evoked Brainstem responses to speech and click stimuli were recorded using Biologic Navigator Pro evoked potential systems (Version-7.0).

Test stimulus:

- A 40 ms duration of /da/ stimulus is a synthesized speech syllable produced using KLATT synthesizer (Klatt, 1980) available in the Biologic Navigator Pro-AEP system was used to record FFR. This stimulus simultaneously contains broad spectral and fast temporal information's characteristic 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) of the /da/ stimulus 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. Figure -3.1 and 3.2 shows the time domain waveform and spectrum respectively of the stimulus /da/ used in the present study.

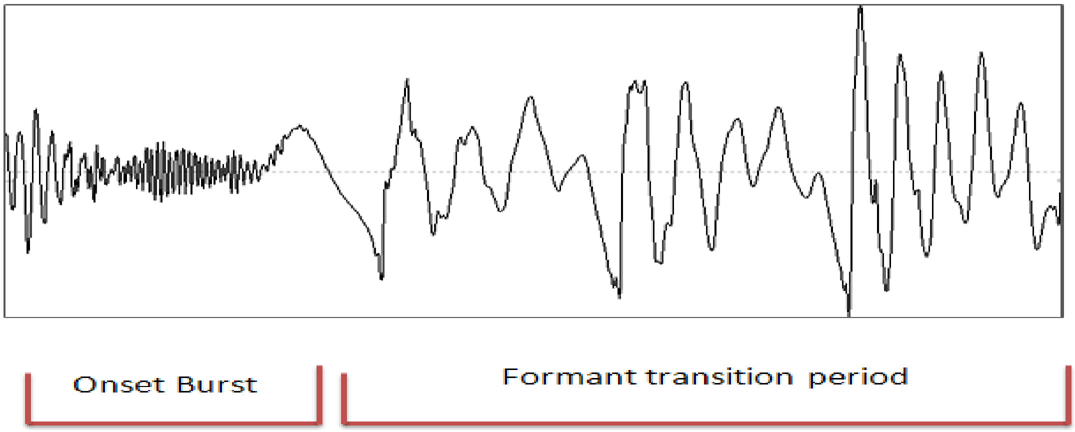

Figure 3.1. Time domain waveform of /da/ stimulus

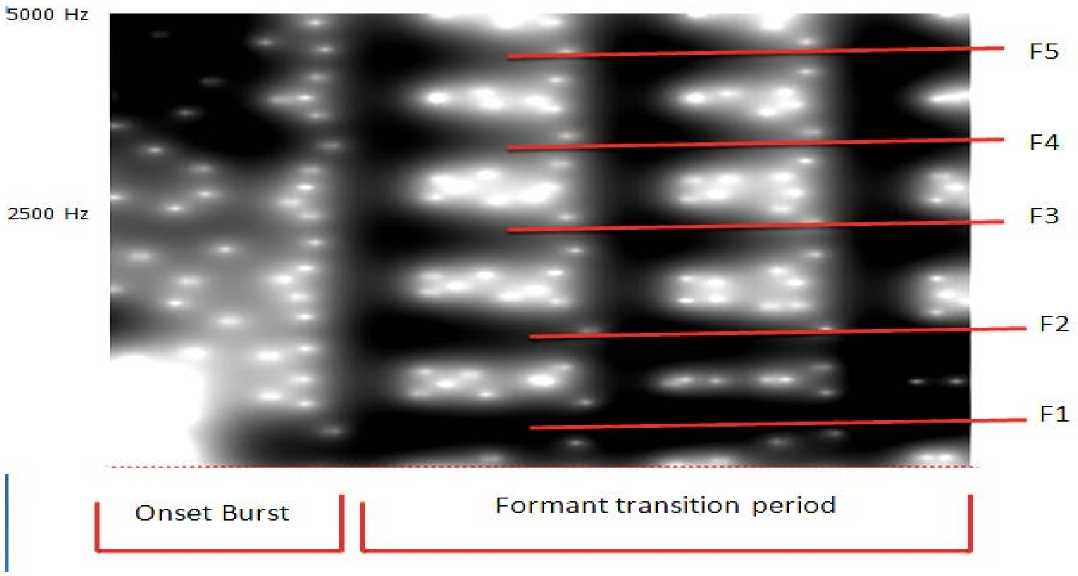

Figure 3.2. Spectrum of stimulus /da/

Test environment

All the tests were carried out in a well illuminated air conditioned rooms which was acoustically treated. The noise levels were within the permissible levels as recommended by ANSI-S.3 (1991).

Test procedure

Screening Checklist for Auditory Processing:

The SCAP developed by Yathiraj and Mascarenhas, (2004) was administered to all the children. The SCAP was administered to rule out any auditory processing problem. This checklist consisted of 12 questions. The detail of the questionnaire is given in the APPENDIX- I. Subjects who have passed the checklist have undergone audiological assessment and also tests required for the study.

Pure tone audiometry:

Pure tone air conduction thresholds for each subject was established in octaves frequencies from 250Hz to 8 KHz using modified Hughson - Westlake method (Carhart & Jerger, 1959). Bone conduction thresholds were also established in octaves frequencies from 250Hz to 4 KHz using the same procedure.

Immittance:

The tympanometric measurements were done using 226 Hz probe tone of 85 dB SPL. For reflex measurements the reflex eliciting tone of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were presented ipsilaterally and contralaterally to find out the presence or absence of acoustic reflexes. A significant change of admittance value of 0.03ml was considered as a presence of reflex.

Procedure to record ABR and FFR:

The subjects were instructed to sit comfortably and relax on a reclining chair facing away from the instrument. They were instructed to avoid movement of head, eyes, neck and limbs during testing to avoid artifacts.

Electrode placement:

Initially the electrode sites were cleaned using skin preparation paste (neoprupe). The silver chloride disc types of electrodes were placed on the scalp at electrode placement site with adequate amount of conduction paste material. The non-inverting electrode was placed on forehead, the inverting electrode was placed on test ear and ground electrode was placed on non-test ear respectively. Then the electrodes were taped to prevent any dislocation of electrodes by means of surgical plaster. ER-3A Insert ear phones were placed in the ear canal to present the stimuli. The parameters used to record ABR is seen in table 3.1.

Table 3.1

Parameters used to record click and Speech evoked ABR

Parameters	Click ABR	Speech ABR
Acquisition Parameters		
Band-pass filter	100-3000Hz	100-3000Hz
Analysis time	10 msec	64 msec which included a prestimulus time of 10 msec (default setting in Biologic system)
Notch filter	On	on
Gain	100000	100000
No. of channels	1	1
Stimulus Parameters		
Stimulus	Click	/da/
Polarity	Alternate	Alternate
Repetition rate	6.9, 10.9 & 15.4 and also 11.1 & 90.1	6.9, 10.9 & 15.4
Intensity	80 dB SPL	80 dB SPL
Total number of stimulus	2000	2000

Click evoked ABR and Speech evoked ABR and FFR were recorded twice from each ear for each repetition rate to ensure the reliability of the waveforms. Click evoked ABR recorded at 11.1/sec and 90.1/sec were used to rule out the presence of retrocochlear pathology. A good wave morphology having wave I, III and V at both the repetition rates and also having normal interpeak interval, was considered as absent of retrochochlear pathology. Click evoked ABR were also recorded at 6.9/sec, 10.9/sec and 15.4/sec used to check the presence of wave V for all the subjects and to check the normal subcortical auditory function. For all the three repetition rate the latency and amplitude of wave V was calculated to check the effect of different repetition rate on normal subcortical auditory function. Speech evoked ABR and FFR were also recorded at 3 repetition rate.

Speech evoked ABR is composed of the transient and the sustained responses (also known as frequency following responses). In the present study latency of both the transient as well as sustained responses were evaluated. Transient response consists of peak V & A latency whereas the sustained responses consists of peaks D, E, F, and O.

Figure 3.3. Speech evoked ABR recorded from one of the individual

For measuring the latency of the sustained responses, the response waveform was shifted 7 msec to compensate for neural lag in the response. The latency of transient as well sustained responses was evaluated as per the guidelines given in the earlier studies

(Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; Russo, Nicloe, Musachia & Kraus, 2004; Hornickel, Skoe, Nicol, Zecker, & Kraus 2009). Amplitude of the Speech ABR was calculated by analyzing the absolute amplitude of the wave V & A and absolute amplitude of the peaks D, E, and F.

Procedure for FFT analysis:

Additionally to know the different aspects of speech that is the coding of fundamental frequency, first formant frequency and higher harmonics an FFT analysis of the sustained response of the speech evoked ABR was done. This was executed using the MATLAB R 2009a platform and software (Brainstem toolbox) developed by Nina Kraus (2004) at Northwestern university. Speech evoked ABR waveforms were first converted into "ASCII" format using the software called 'AEP TO ASCII'. ASCII format data then analyzed using 'BRAINSTEM TOOLBOX' developed at Northwestern University. This software runs on MATLAB platform and does the FFT of the waveforms and analyses the FFR.

Fourier analysis is performed on the 11.4 – 40.6 ms epoch of the FFR to extract the information regarding the coding of fundamental frequency, first formant frequency and second formant frequency at each repetition rate in order to assess the amount of activity occurred at all these three frequencies. Activity occurred in the frequency range of the response corresponding to the fundamental frequency of the speech stimulus (103– 121 Hz), first formant frequencies of the stimulus (454- 719 Hz) and for the higher harmonics (721-1155 Hz) was measured for all the subjects. This was done as per the guidelines given in earlier studies (Cunningham et al., 2001; Russo et al., 2004; Hornickel, et al., 2009; Johnson, Nicol, Zecker, & Kraus, 2008). A 2 ms on 2 m off Hanning ramp was applied to the waveform (this is done to prevent the frequency splattering during the Fourier analysis). Zero-padding was employed to increase the number of frequency points where spectral estimates were obtained. An auditory evoked response from the subjects was required to be above the noise floor in order to be included in the analyses (Russo et al., 2004). This calculation was performed by comparing the spectral magnitude of the pre-stimulus period to that of the response (Russo et al., 2004). If the quotient of the magnitude of the F0, F1 and higher harmonics frequency component of the FFR divided by that of the prestimulus period was greater than or equal to one, the response was deemed above the noise floor (Russo et al., 2004). The raw amplitude value of the F0 or F1 frequency and higher frequency component of the response FFR were then measured.

Analysis:

To compare and check for developmental changes:

- Latency and amplitude of wave V of click evoked ABR were compared
- Latency and amplitude of wave V and A of speech evoked ABR were compared
- Latency and amplitude of wave D, E, and F of Speech evoked FFR were compared (The distance between the peak D, E, and F is approximately 10 msec which gives the information regarding the encoding of fundamental frequency).
- Extracted information regarding the coding of fundamental frequency, first formant frequency and second formant frequency for speech evoked ABR at different repetition rates were also compared.

Chapter-4

Results

The brainstem responses to click and speech stimulus were recorded at 80 dB SPL across three repetition rates (6.9, 10.9 & 15.4). The wave – V, A, D, E and F were identified and their latency and amplitude were noted. Fast Fourier Transforms were done to find the raw amplitude of FO, F1 and higher harmonics (F2) frequency components elicited by syllable /da/ using custom made program run on a MATLAB platform. The mean and 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 groups and also within the group of children.

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

1. Mixed ANOVA was done to see the significant interaction across the five groups and three repetition rates for the following parameters:
    - Wave V latency and amplitude for click evoked ABR
    - Wave V and A latency and amplitude for speech evoked ABR
    - Wave D, E and F (FFR) latency and amplitude for speech evoked FFR
    - F0, F1 and higher harmonics (F2) amplitude elicited by syllable /da/
2. MANOVA was done across the group to see the significant difference in data obtained across the repetition rates as the Mixed ANOVA showed interaction between groups and repetition rates by considering data from all the groups for Wave E latency evoked by syllable /da/

3. Repeated measure ANOVA was done within the group to see significant difference in data obtained across the repetition rates as the Mixed ANOVA showed a significant interaction across the repetition rates by considering data from all the groups for the following parameters:
    - Wave V latency for click evoked ABR
    - Wave V and A latency and wave V amplitude for speech evoked ABR
    - Wave D, E and F (FFR) latency and wave E and F amplitude for speech evoked FFR
    - F1 amplitude elicited by syllable /da/
4. Bonferroni post hoc test was done where Mixed ANOVA or repeated ANOVA show significant interaction. A paired t-test was done as Bonferroni post hoc test did not show significant difference though repeated measures ANOVA showed significant difference, for the following parameters:
    - Wave V latency of click evoked ABR for the group IV across the three repetition rates
    - F1 amplitude elicited by syllable /da/ for the group IV across the three repetition rates

Latency of Click evoked ABR:

The latency of wave V was analysed for the click evoked ABR across the three different repetition rates (6.9, 10.9 & 15.4). Figure- 4.1 shows a ABR waveform elicited by click at three repetition rates in a normal hearing subject.

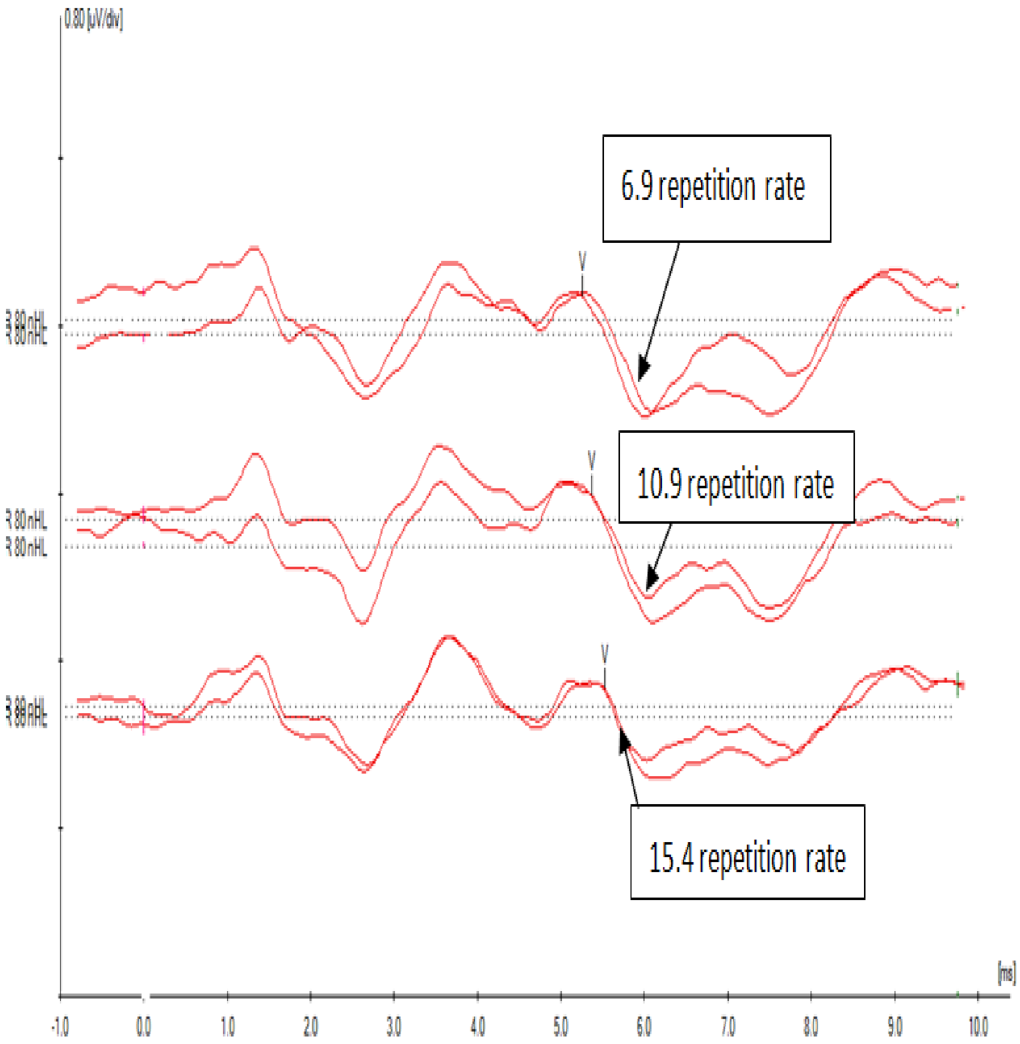

Figure 4.1. Click evoked ABR recorded at three different repetition rates.

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 rates increased.

Table 4.1

Mean and Standard deviations (S.D) of click evoked ABR wave V latency obtained at three repetition rates across the groups

Peak	Age → Groups	5-5.11 years		6-6.11 years		7-7.11years		8-8.11years		9-9.11 years	
	Repetition ↓ rates	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
Wave V	6.9	5.31	0.23	5.22	0.27	5.41	0.14	5.22	0.23	5.29	0.29
	10.9	5.31	0.23	5.22	0.27	5.39	0.13	5.24	0.22	5.29	0.28
	15.4	5.32	0.25	5.27	0.21	5.40	0.14	5.28	0.18	5.33	0.26

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

Effect of repetition rate and age on latency of click evoked ABR wave V

To see the effects of repetition rates and age on latency of click evoked ABR Wave V, Mixed ANOVA (3 repetition rates and 5 groups) was done. The results of the Mixed ANOVA did not show any significant interaction across the groups [$F(4, 52) = 1.01$, $p>0.05$] and also groups and repetition rates [$F(8, 104) = 1.30$, $p>0.05$]. However, a significant interaction across the repetition rates [$F(2, 104) = 8.75$, $p< 0.05$] was observed. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates wave V latency, differ significantly from each other. Details of the Bonferroni post hoc test is shown in table 4.2.

Table 4.2

Bonferroni Post Hoc Test results for the Wave V latency of Click evoked ABR across the three repetition rates

Repetition rate	10.9	15.4
6.9	No Significant $p>0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, repeated measure ANOVA (3 repetition rates) was done within the group to see which group had significant difference in wave V latency across the repetition rates. Repeated-measures analysis of variance (ANOVA) test results showed that there is no significant difference across the three repetition rates for group I [F (2, 18) = 0.45, $p>0.05$], group II [F (2, 20) = 3.20, $p>0.05$], group III [F (2, 24) = 0.73, $p>0.05$] and also group V [F2, 18) = 2.52, $p>0.05$].

However, the results showed that there is a significant difference across the three repetition rates for group IV [F (2, 24) = 4.44, $p<0.05$]. As the repeated measure ANOVA showed significant difference across the repetition rates for the group IV. Bonferroni post hoc test was done to see between which two repetition rates wave V latency, differed significantly. Details of the Bonferroni post hoc test is shown in table 4.3.

Table 4.3

Bonferroni Post Hoc Test results for the Wave V latency of click evoked ABR across the three repetition rates for group IV

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	No Significant p>0.05
10.9		No Significant p>0.05

A paired t-test was done as Bonferroni post hoc test showed no significant difference, though repeated measures ANOVA showed significant difference, for Wave V latency of click evoked ABR for the group IV across the three repetition rates. A paired t-test results showed significant difference between wave V latency obtained at 6.9 and 10.9 [t (12) = 2.55, p<0.05] and also at 6.9 and 15.4 [t (12) = 2.24, p<0.05] repetition rates. However, it did not show significant difference between wave V latency obtained at 10.9 and 15.4 [t (12) = 1.83, p>0.05] repetition rates.

Latency of Speech evoked ABR and FFR waves:

The latency of wave V, A, D, E and F were analysed for the speech evoked ABR and FFR for three different repetition rates (6.9, 10.9 & 15.4). Figure- 4.2 Shows syllable /da/ evoked ABR and FFR waveform at three repetition rates obtained from one of the normal hearing subject.

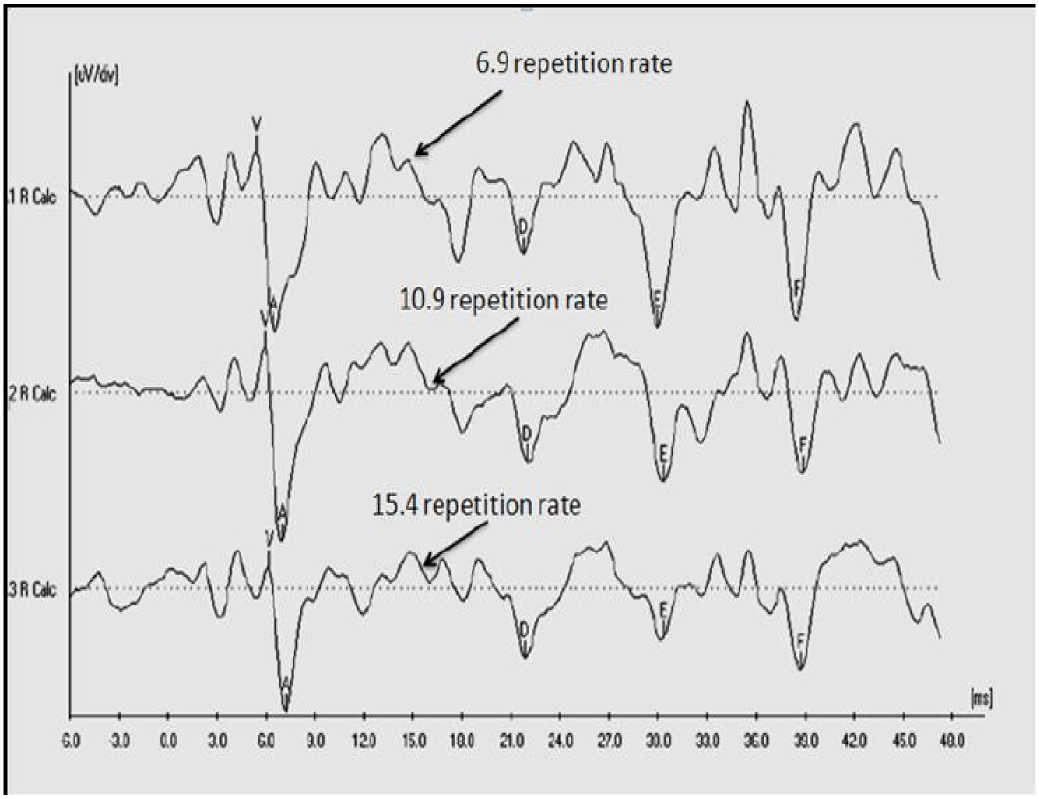

Figure 4.2. Speech evoked ABR and FFR recorded at three different repetition rates.

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 and FFR with the increased in repetition rates. The mean latency of speech evoked transient response and sustained response also showed similar changes with the repetition rates. The following figures show the mean latency of speech evoked transient response and sustained response across the repetition rates and groups:

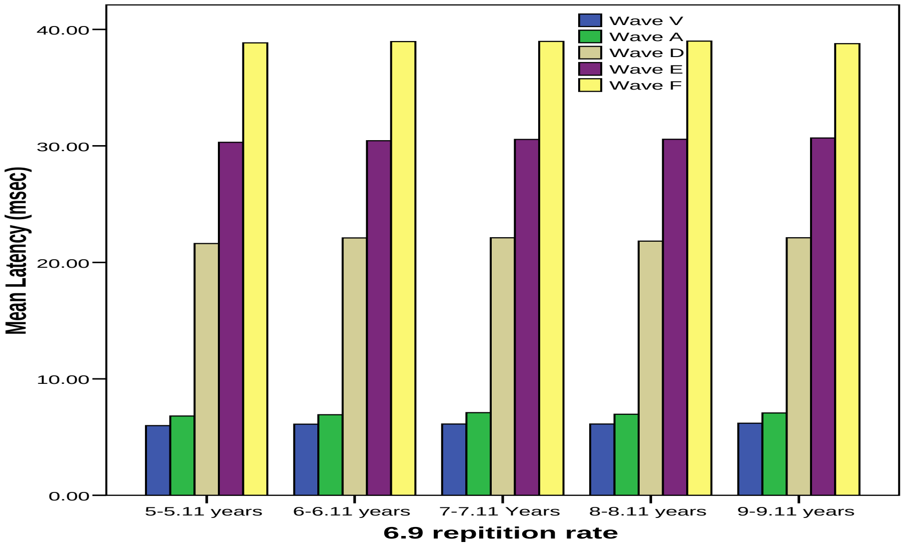

Figure 4.3. Latencies obtained at 6.9 repetition rate of speech evoked transient and sustained wave responses across the groups

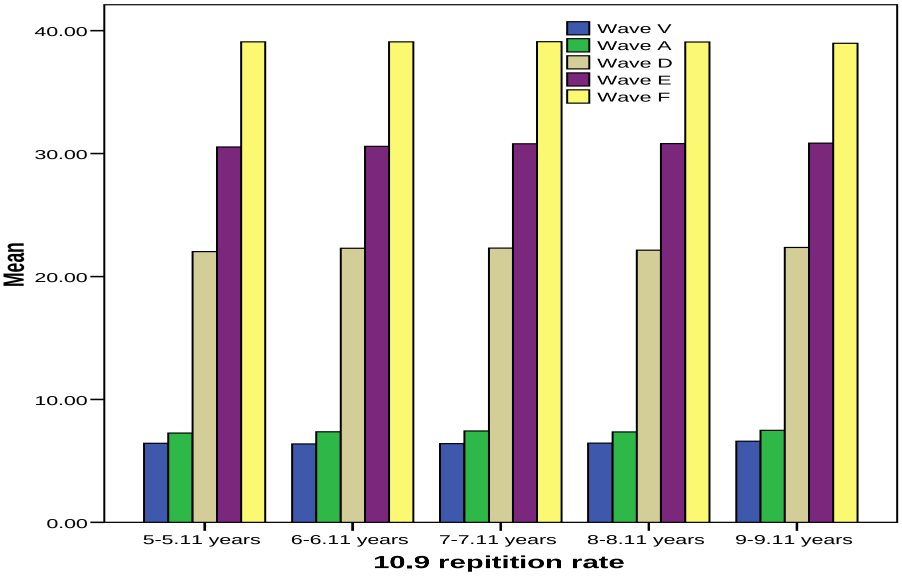

Figure 4.4. Latencies obtained at 10.9 repetition rate of speech evoked transient and sustained responses across the groups

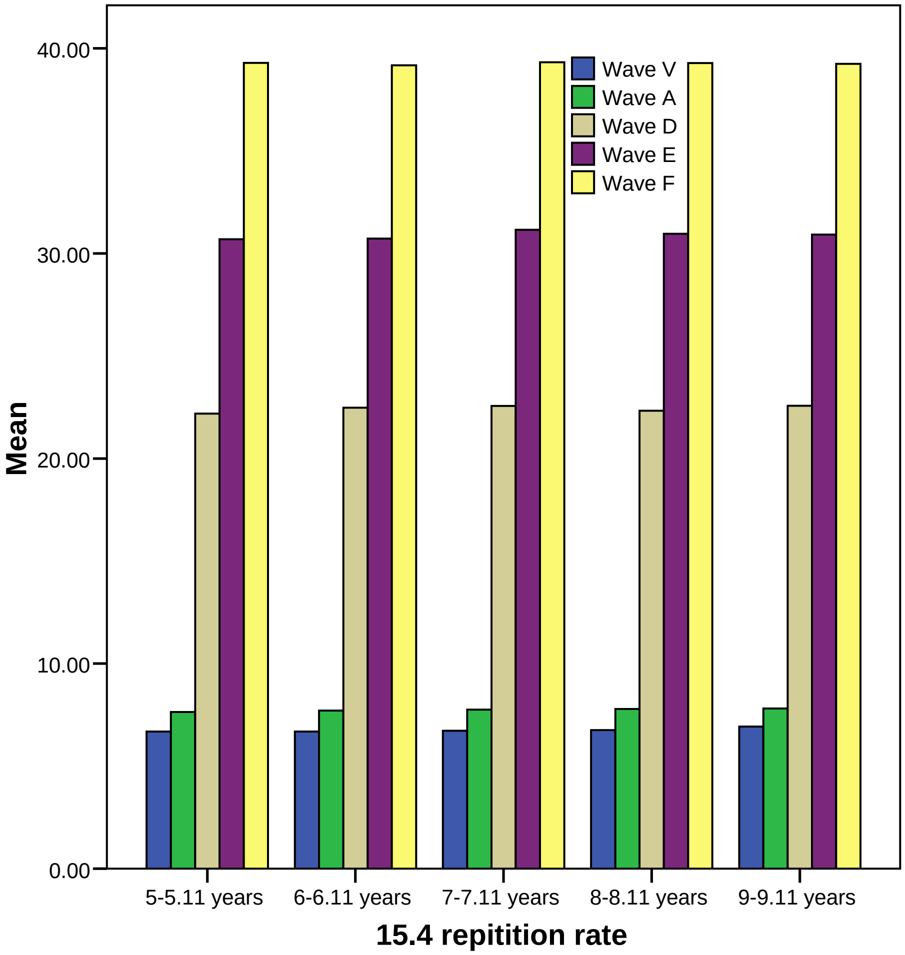

Figure 4.5. Latencies obtained at 15.4 repetition rate of speech evoked transient and sustained responses across the groups

Table 4.4

Mean and Standard deviations (S.D) of different speech evoked ABR and FFR wave latencies obtained at three repetition rates across the groups

Peak	Age → Groups	5-5.11 years		6-6.11 years		7-7.11years		8-8.11years		9-9.11 years	
	Repetition rates ↓	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
Wave V	6.9	5.98	0.30	6.11	0.32	6.11	0.21	6.11	0.25	6.19	0.20
	10.9	6.43	0.30	6.38	0.31	6.40	0.34	6.45	0.27	6.59	0.19
	15.4	6.69	0.33	6.68	0.34	6.73	0.33	6.76	0.33	6.93	0.20
Wave A	6.9	6.80	0.23	6.92	0.47	7.09	0.42	6.95	0.31	7.07	0.20
	10.9	7.26	0.26	7.36	0.47	7.42	0.37	7.35	0.37	7.49	0.21
	15.4	7.64	0.29	7.71	0.44	7.75	0.32	7.78	0.32	7.81	0.15
Wave D	6.9	21.62	0.31	22.10	0.59	22.11	0.55	21.82	0.84	22.11	0.60
	10.9	22.01	0.52	22.29	0.59	22.31	0.47	22.14	0.85	22.35	0.48
	15.4	22.18	0.51	22.48	0.64	22.56	0.47	22.33	0.85	22.56	0.47
Wave E	6.9	30.30	0.47	30.44	0.54	30.56	0.67	30.57	0.51	30.67	0.38
	10.9	30.53	0.43	30.58	0.50	30.79	0.65	30.81	0.62	30.84	0.39
	15.4	30.69	0.37	30.72	0.40	31.15	0.80	30.96	0.60	30.92	0.35
Wave F	6.9	38.85	0.30	38.95	0.46	38.97	0.35	38.99	0.30	38.77	1.29
	10.9	39.08	0.33	39.08	0.40	39.09	0.35	39.06	0.31	38.97	1.35
	15.4	39.29	0.44	39.17	0.43	39.32	0.35	39.28	0.32	39.24	1.36

The mean and the standard deviations of the different wave latencies were calculated for the speech evoked ABR and FFR recorded at three repetition rates. The mean and standard deviation values obtained are given in table 4.4. It can be seen from the table 4.4 that, as the repetition rate increased, there is an increase in latency of all the peaks of speech evoked transient response and FFR. However, shift for transient response was more than the shift noticed for FFR waves.

Effect of repetition rate and age on latency of /da/ evoked transient and FFR waves

Latency of Transient response

To see the effects of repetition rates and age on the latency of transient response elicited by syllable /da/ Mixed ANOVA (3 repetition rates and 5 groups) was done. The results for each transient wave are discussed below.

Wave V: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.82, $p>0.05$] and also groups and repetition rates [F (8, 104) = 1.37, $p>0.05$]. However, there was a significant interaction across the repetition rates [F (2, 104) = 451.64, $p< 0.05$] for wave V latency. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates for wave V latency differ significantly. Details of the Bonferroni post hoc test is shown in table 4.5.

Table 4.5

Bonferroni Post Hoc Test results for the /da/ evoked Wave V latency across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant p<0.05	Significant p<0.05
10.9	▨	Significant p<0.05

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave V latency across the repetition rates. Repeated-measures analysis of variance (ANOVA) test results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 90.22, p<0.05], group II [F (2, 20) = 98.76, p<0.05], group III [F (2, 24) = 52.79, p<0.05], group IV [F (2, 24) = 126.34, p<0.05] and also group V [F (2, 18) = 177.39, p<0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for all the groups, Bonferroni post hoc test was done to see, which two repetition rates wave V latency, differed significantly. The results obtained from Bonferroni post hoc test for all the group showed the same results. Details of the Bonferroni post hoc test is shown in table 4.6.

Table 4.6

Bonferroni Post Hoc Test results for the /da/ evoked Wave V latency across the three repetition rates for all the groups

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Wave A: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.77, $p>0.05$] and also groups and repetition rates [F (8, 104) = 0.68, $p>0.05$]. However, significant interaction was obtained across the repetition rates [F (2, 104) = 277.36, $p< 0.05$] for wave A latency. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done. Details of the Bonferroni post hoc test is shown in table 4.7.

Table 4.7

Bonferroni Post Hoc Test results for the /da/ evoked Wave A latency across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Repeated measure ANOVA (3 repetition rates) was done separately for each group to see, which group had significant difference in wave A latency across the repetition rates. The results showed that there is a significant difference across the three repetition rates for group

I [F (2, 18) = 50.38, p<0.05], group II [F (2, 20) = 61.81, p<0.05], group III [F (2, 24) = 28.14, p<0.05], group IV [F (2, 24) = 113.20, p<0.05] and also group V [F (2, 18) = 93.57, p<0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for all the groups, Bonferroni post hoc test was done to see, which two repetition rates wave A latency, differed significantly from each other. The results obtained from Bonferroni post hoc test for all the group showed the same results. Details of the Bonferroni post hoc test is shown in table 4.8.

Table 4.8

Bonferroni Post Hoc Test results for the /da/ evoked Wave A latency across the three repetition rates for all the groups

Repetition rate	10.9	15.4
6.9	Significant p<0.05	Significant p<0.05
10.9		Significant p<0.05

Latency of the sustained responses (FFR of speech evoked ABR)

To see the effects of repetition rates and age on latency of sustained response elicited by syllable /da/ Mixed ANOVA (3 repetition rates and 5 groups) was done. The results for each sustained wave are discussed below.

Wave D: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.92, p>0.05] and also groups and repetition rates [F (8, 104) = 0.86, p>0.05] for wave D latency. However, it did show significant interaction across the repetition rates [F (2, 104) = 104.02, p< 0.05]. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates for wave D latency differ significantly from each other. Details of the Bonferroni post hoc test is shown in table 4.9.

Table 4.9

Bonferroni Post Hoc Test results for the /da/ evoked Wave D latency across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, repeated measure ANOVA (3 repetition rates) was done for each group to see which group had significant difference in wave D latency across the repetition rates. The results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 20.57, $p<0.05$], group II [F (2, 20) = 22.15, $p<0.05$], group III [F (2, 24) = 18.88, $p<0.05$], group IV [F (2, 24) = 26.44, $p<0.05$] and also group V [F (2, 18) = 21.86, $p<0.05$]. As the repeated measure ANOVA showed significant difference across the repetition rates for all the groups. Bonferroni post hoc test was done. The results obtained from Bonferroni post hoc test for all the group showed the same results. Details of the Bonferroni post hoc test is shown in table 4.10.

Table 4.10

Bonferroni Post Hoc Test results for the /da/ evoked Wave D latency across the three repetition rates for all the groups

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Wave E: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.92, $p>0.05$] for wave E latency. However, it did show significant interaction for groups and repetition rates [F (8, 104) = 0.86, $p>0.05$] and also across the repetition rates [F (2, 104) = 104.02, $p< 0.05$]. Bonferroni post hoc test was done to see which two repetition rates for wave E latency differ significantly from each other. Details of the Bonferroni post hoc test is shown in table 4.11.

Table 4.11

Bonferroni Post Hoc Test results for the /da/ evoked Wave E latency across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

As the Mixed ANOVA showed significant interaction between groups and repetition rates. MANOVA was done to see which repetition rates had significant difference in wave E latency across the groups. No significant difference was seen for the repetition rates of 6.9 [F

(4, 52) = .70, p>0.05), 10.9 [F (4, 52) = .75, p>0.05] and at 15.4 [F (4, 52) = 1.29, p>0.05].

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, 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-measures analysis of variance (ANOVA) test results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 31.64, p<0.05], group II [F (2, 20) = 5.32, p<0.05], group III [F (2, 24) = 31.29, p<0.05] and also group IV [F (2, 24) = 19.40, p<0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for group I, II, III and IV, Bonferroni post hoc test was done for group I, II, III and IV. Details of the Bonferroni post hoc test is shown in table 4.12, 4.13 and 4.14 as all the groups did not show similar results.

Table 4.12

Bonferroni Post Hoc Test results for the /da/ evoked Wave E latency across the three repetition rates for group I & III

Repetition rate	10.9	15.4
6.9	Significant p<0.05	Significant p<0.05
10.9		Significant p<0.05

Table 4.13

Bonferroni Post Hoc Test results for the /da/ evoked Wave E latency across the three repetition rates for group II

Repetition rate	10.9	15.4
6.9	Significant p<0.05	No Significant p>0.05
10.9		No Significant p>0.05

Table 4.14

Bonferroni Post Hoc Test results for the /da/ evoked Wave E latency across the three repetition rates for group IV

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		No Significant $p>0.05$

Repeated-measures analysis of variance (ANOVA) test results however did not show any significant difference across the three repetition rates for group V [F (2, 18) = 6.33, $p>0.05$]. Hence Bonferroni post hoc test was not administered.

Wave F- For wave F Mixed ANOVA results did not show any significant interaction across the groups [F (4, 52) = 0.77, $p>0.05$] and also groups and repetition rates [F (8, 104) = 1.26, $p>0.05$]. However, a significant interaction across the repetition rates [F (2, 104) = 63.97, $p< 0.05$] was observed. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done. Details of the Bonferroni post hoc test is shown in table 4.15.

Table 4.15

Bonferroni Post Hoc Test results for the /da/ evoked Wave F latency across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

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. The results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 26.04, $p<0.05$], group II [F (2, 20) = 3.88, $p<0.05$], group III [F (2, 24) = 11.65, $p<0.05$], group IV [F (2, 24) = 8.73, $p<0.05$] and also group V [F (2, 18) = 48.16, $p<0.05$]. As the repeated measure ANOVA showed significant difference across the repetition rates for group I, II, III, IV and group V, Bonferroni post hoc test was done for all the groups. Details of the Bonferroni post hoc test is shown in table 4.16, 4.17 and 4.18 as all the groups showed different results.

Table 4.16

Bonferroni Post Hoc Test results for the /da/ evoked Wave F latency across the three repetition rates for group I & V

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Table 4.17

Bonferroni Post Hoc Test results for the /da/ evoked Wave F latency across the three repetition rates for group II

Repetition rate	10.9	15.4
6.9	No Significant $p>0.05$	No Significant $p>0.05$
10.9		Significant $p<0.05$

Table 4.18

Bonferroni Post Hoc Test results for the /da/ evoked Wave F latency across the three repetition rates for group III & IV

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	Significant p<0.05
10.9		Significant p<0.05

Amplitude:

The amplitude for click evoked ABR, speech evoked ABR, FFR and Harmonics (F0, F1 & F2) were noted at three repetition rates. The data were subjected to statistical analysis to observe the significant effect of rate and age on different non-speech and speech evoked ABR and FFR waves. The results of different parameters are discussed one by one.

Amplitude of Click evoked ABR:

The mean amplitude of click evoked ABR wave V was calculated at three different repetition rates across the group. The amplitude of click evoked ABR wave V are shown in figure 4.6.

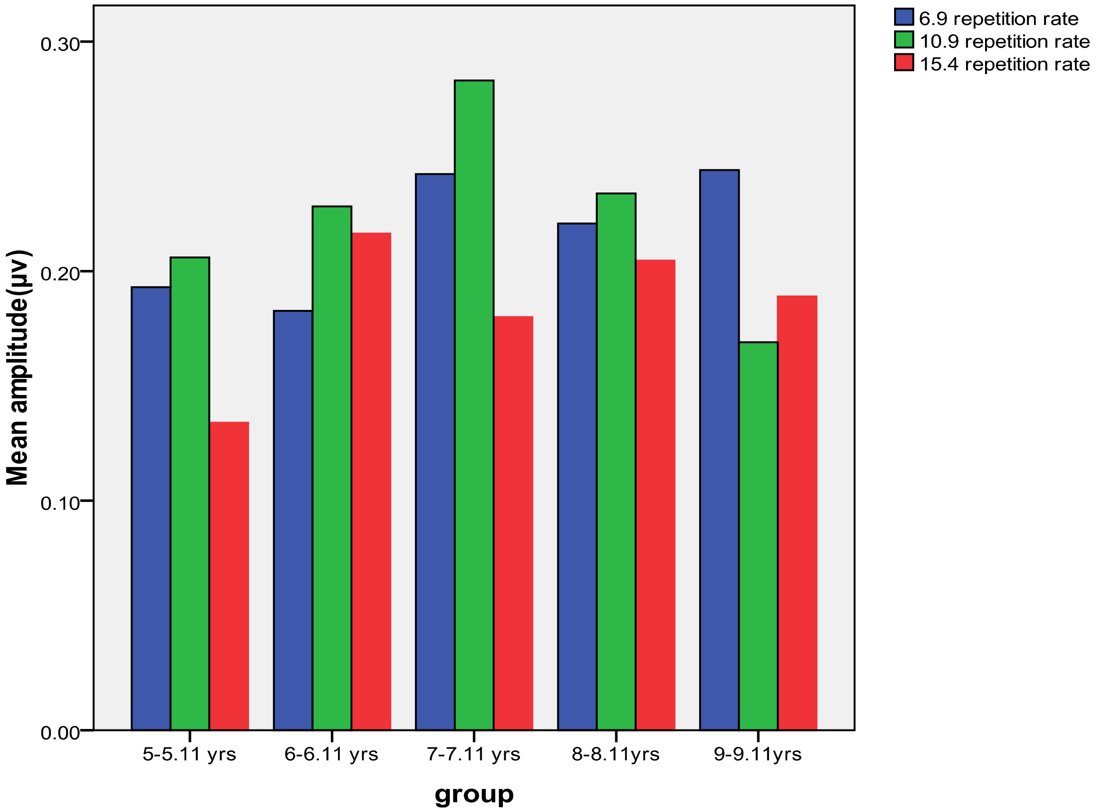

Figure 4.6. Mean amplitude of click evoked ABR wave V across rates and groups

Table 4.19

Mean and Standard deviations (S.D) of click evoked ABR wave V amplitude obtained at three repetition rates across the groups

Peak	Age → Groups	5-5.11 years		6-6.11 years		7-7.11years		8-8.11years		9-9.11 years	
	Repetition ↓ rates	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
Wave V	6.9	0.19	0.10	0.18	0.08	0.24	0.13	0.22	0.9	0.24	0.11
	10.9	0.20	0.11	0.22	0.16	0.28	0.16	0.23	0.10	0.16	0.09
	15.4	0.13	0.10	0.21	0.07	0.18	0.06	0.20	0.13	0.18	0.09

The mean and the standard deviations of the wave V amplitude were calculated for the click evoked ABR wave V recorded at three repetition rates. The mean and standard deviation values obtained are given in table 4.19. It can be seen from the table 4.19 and figure 4.6 that, wave V amplitude did not show any specific trend with the change in repetition rate. However, most of group have show a reduced wave V amplitude obtained at 15.4 rate, compare to that obtained at 6.9 repetition rate.

Effect of repetition rate and age on amplitude of click evoked ABR wave V

To see the effects of repetition rates and age on amplitude of click evoked ABR Wave V, Mixed ANOVA (3 repetition rates and 5 groups) was done. The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.75, p>0.05] groups and repetition rates [F (8, 104) = 1.23, p>0.05] and also across the repetition rates [F (2, 104) = 2.56, p> 0.05]. Thus further statistical analysis was not done.

Amplitude of Speech evoked ABR:

The amplitude of wave V, A, D, E and F were analysed for the speech evoked ABR and FFR for three different repetition rates (6.9, 10.9 & 15.4). The mean amplitude of speech evoked ABR and FFR was calculated. The following figures depict the mean amplitude of speech evoked transient and sustained response obtained across the repetition rates and groups.

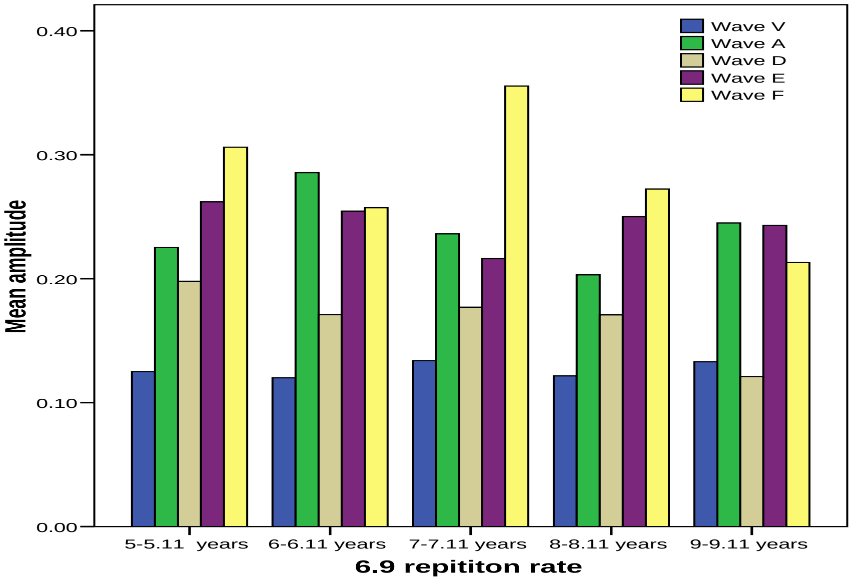

Figure 4.7. Mean amplitude of speech evoked transient and sustained waves obtained at 6.9 repetition rate across the groups

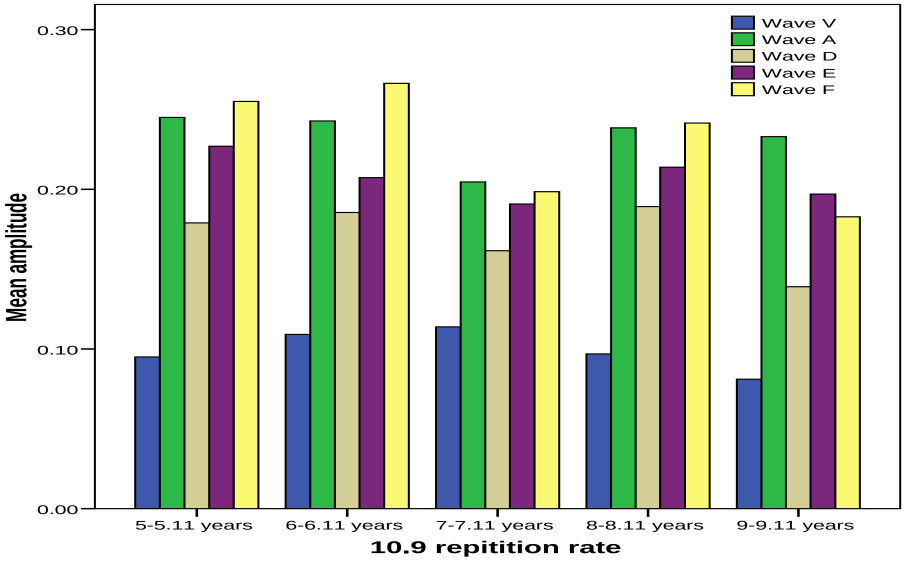

Figure 4.8. Mean amplitude of speech evoked transient and sustained waves obtained at 10.9 repetition rate across the groups

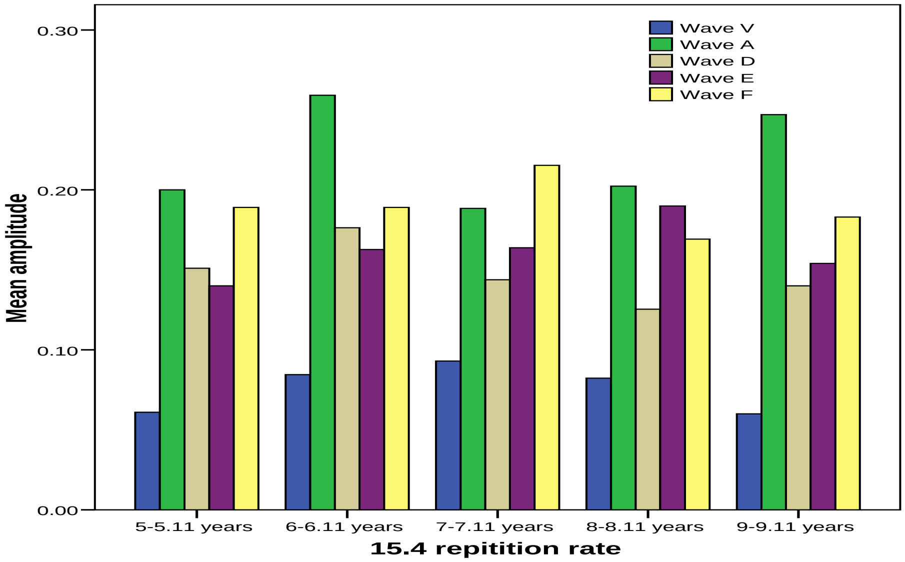

Figure 4.9. Mean amplitude of speech evoked transient and sustained waves obtained at 15.4 repetition rate across the groups

Table 4.20

Mean and Standard deviations (S.D) of different speech evoked transient and FFR waves amplitude obtained at three repetition rates across the groups

Peak	Age Groups →	5-5.11 years		6-6.11 years		7-7.11years		8-8.11years		9-9.11 years	
	Repetition rates ↓	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
Wave V	6.9	0.12	0.07	0.12	0.07	0.13	0.06	0.12	0.05	0.13	0.05
	10.9	0.09	0.06	0.10	0.05	0.11	0.06	0.09	0.04	0.08	0.04
	15.4	0.06	0.03	0.08	0.02	0.09	0.06	0.08	0.05	0.06	0.03
Wave A	6.9	0.22	0.11	0.28	0.11	0.23	0.11	0.20	0.12	0.22	0.06
	10.9	0.24	0.06	0.24	0.11	0.20	0.09	0.23	0.11	0.23	0.05
	15.4	0.20	0.06	0.25	0.09	0.18	0.06	0.20	0.04	0.24	0.09
Wave D	6.9	0.19	0.12	0.17	0.08	0.17	0.10	0.17	0.08	0.12	0.06
	10.9	0.17	0.07	0.18	0.05	0.16	0.06	0.18	0.09	0.13	0.07
	15.4	0.15	0.06	0.17	0.05	0.14	0.07	0.12	0.07	0.14	0.03
Wave E	6.9	0.26	0.06	0.25	0.10	0.21	0.08	0.25	0.15	0.24	0.09
	10.9	0.22	0.05	0.20	0.13	0.19	0.08	0.21	0.11	0.19	0.08
	15.4	0.14	0.06	0.16	0.06	0.16	0.05	0.19	0.07	0.15	0.09
Wave F	6.9	0.30	0.14	0.25	0.16	0.35	0.36	0.27	0.15	0.21	0.10
	10.9	0.25	0.11	0.26	0.11	0.19	0.07	0.24	0.13	0.18	0.13
	15.4	0.18	0.09	0.18	0.13	0.21	0.09	0.16	0.10	0.18	0.12

The mean and the standard deviations of the different wave amplitude were calculated for the speech evoked ABR and FFR, recorded at three repetition rates. The mean and standard deviation values obtained are given in table 4.20. It can be seen from the table 4.20 and also figure 4.7 to 4.9 that, as the repetition rate increased, there is a decrease in amplitude of all most all the peaks of speech evoked transient and FFR waves in all the groups.

Effect of repetition rate and age on amplitude of /da/ evoked transient and FFR waves across groups.

Amplitude of Transient response

To see the effects of repetition rates and age on amplitude of transient response elicited by syllable /da/ Mixed ANOVA (3 repetition rates and 5 groups) was done. The results for each transient wave are discussed below.

Wave V: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.52, $p>0.05$] and also groups and repetition rates [F (8, 104) = 0.46, $p>0.05$]. However, there was a significant interaction across the repetition rates [F (2, 104) = 16.96, $p< 0.05$]. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates for wave V amplitude, differ significantly from each other. Details of the Bonferroni post hoc test is shown in table 4.21.

Table 4.21

Bonferroni Post Hoc Test results for the /da/ evoked Wave V amplitude across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant p<0.05	Significant p<0.05
10.9		Significant p<0.05

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, repeated measure ANOVA (3 repetition rates) was done within the group to see which group had significant difference in wave V amplitude across the repetition rates. Repeated-measures analysis of variance (ANOVA) test results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 7.79, $p<0.05$], group IV [F (2, 44) = 7.98, $p<0.05$] and also group V [F (2, 18) = 9.13, $p<0.05$]. As the repeated measure ANOVA showed significant difference across the repetition rates for group I, group IV and also group V. Bonferroni post hoc test was done to see between which two repetition rates wave V amplitude, differed significantly. Details of the Bonferroni post hoc test results is shown in table 4.22 and 4.23 as all the groups did not show similar results.

Table 4.22

Bonferroni Post Hoc Test results for the /da/ evoked Wave V amplitude across the three repetition rates for group I

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	Significant p<0.05
10.9		No Significant p>0.05

Table 4.23

Bonferroni Post Hoc Test results for the /da/ evoked Wave V amplitude across the three repetition rates for group IV & V

Repetition rate	10.9	15.4
6.9	Significant p<0.05	Significant p<0.05
10.9		No Significant p>0.05

However, group II [F (2, 20) = 1.82, p>0.05] and also group III [F (2, 24) = 2.01, p>0.05] have failed to show any significant difference. Thus, Bonferroni post hoc test was not administered.

Wave A: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.93, p>0.05] groups and repetition rates [F (8, 104) = 1.07, p>0.05] and also across the repetition rates [F (2, 104) = 0.96, p> 0.05]. Thus Bonferroni post hoc test was not carried out.

Amplitude of the sustained responses (FFR of speech evoked ABR)

Mixed ANOVA was carried out (3 repetition rates and 5 groups) to see the significant interaction across the group and also repetition rates for wave D, E and F amplitude. The results obtained are explained below.

Wave D: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.76, $p>0.05$] groups and repetition rates [F (8, 104) = 1.12, $p>0.05$] and also across the repetition rates [F (2, 104) = 2.85, $p>0.05$] for wave D amplitude. Thus, Bonferroni post hoc test was not carried out.

Wave E: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.21, $p>0.05$] and also groups and repetition rates [F (8, 104) = 1.02, $p>0.05$]. However, significant interaction was obtained across the repetition rates [F (2, 104) = 35.78, $p< 0.05$] for wave E amplitude. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates for wave E amplitude differ significantly from each other. Details of the Bonferroni post hoc test is shown in table 4.24.

Table 4.24

Bonferroni Post Hoc Test results for the /da/ evoked Wave E amplitude across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant $p<0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Repeated measure ANOVA (3 repetition rates) was done separately for each group to see which group had significant difference in wave E amplitude across the repetition rates. The results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 26.83, p<0.05], group II [F (2, 20) = 7.00, p<0.05], group III [F (2, 24) = 5.14, p<0.05] and also group V [F (2, 20) = 7.38 p<0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for group I, group II, group III and also group V. Bonferroni post hoc test was done to see between which two repetition rates wave E amplitude, differed significantly. Details of the Bonferroni post hoc test results for each groups are given in table 4.25 and 4.26.

Table 4.25

Bonferroni Post Hoc Test results for the /da/ evoked Wave E amplitude across the three repetition rates for group I

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	Significant p<0.05
10.9		Significant p<0.05

Table 4.26

Bonferroni Post Hoc Test results for the /da/ evoked Wave E amplitude across the three repetition rates for group II, III & V

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	Significant p<0.05
10.9		No Significant p>0.05

However, group IV [F (2, 26) = 3.15, p>0.05] have failed to show any significant difference. Hence, Bonferroni post hoc test was not administered.

Wave F: The Mixed ANOVA results again did not show any significant interaction across the groups [F (4, 52) = 0.40, p>0.05] and also groups and repetition rates [F (8, 104) = 1.27, p>0.05] for wave F amplitude. However significant interaction was obtained across the repetition rates [F (2, 104) = 9.78, p< 0.05]. Bonferroni post hoc test was administered. Details of the Bonferroni post hoc test is shown in table 4.27.

Table 4.27

Bonferroni Post Hoc Test results for the /da/ evoked Wave F amplitude across the three repetition rates

Repetition rate	10.9	15.4
6.9	No Significant p>0.05	Significant p<0.05
10.9	▨	Significant p<0.05

Repeated measure ANOVA (3 repetition rates) was done separately for each group to see which group had significant difference in wave F amplitude across the repetition rates. The results showed that there is a significant difference across the three repetition rates for group I [F (2, 18) = 13.16 p<0.05], group II [F (2, 20) = 4.51, p<0.05] and also group IV [F (2, 24) = 5.92, p<0.05]. As the repeated measure ANOVA showed significant difference across the repetition rates for group I, group II and group IV, Bonferroni post hoc test was done for the three groups. The results obtained from Bonferroni post hoc test for group I, and group IV showed the similar pattern. Details of the Bonferroni post hoc test results are shown in table 4.28 and 4.29.

Table 4.28

Bonferroni Post Hoc Test results for the /da/ evoked Wave F amplitude across the three repetition rates for group I & IV

Repetition rate	10.9	15.4
6.9	No Significant $p>0.05$	Significant $p<0.05$
10.9		Significant $p<0.05$

Table 4.29

Bonferroni Post Hoc Test results for the /da/ evoked Wave F amplitude across the three repetition rates for group II

Repetition rate	10.9	15.4
6.9	No Significant $p>0.05$	No Significant $p>0.05$
10.9		Significant $p<0.05$

However, group III [F (2, 24) = 2.44, $p>0.05$] and also group V [F (2, 18) = 1.56, $p>0.05$] failed to show any significant difference. Thus, further statistical analysis was not done.

Amplitude of F0, F1 and Higher harmonics (F2)

The amplitude of F0, F1 and Higher Harmonics (F2) was analysed for the speech evoked ABR for three different repetition rates (6.9, 10.9 & 15.4). The amplitude of F0, F1 and

Higher harmonics (F2) decreased as the repetition rate increased. The mean amplitude of F0, F1 and Higher harmonics across the five groups are shown in the following figures:

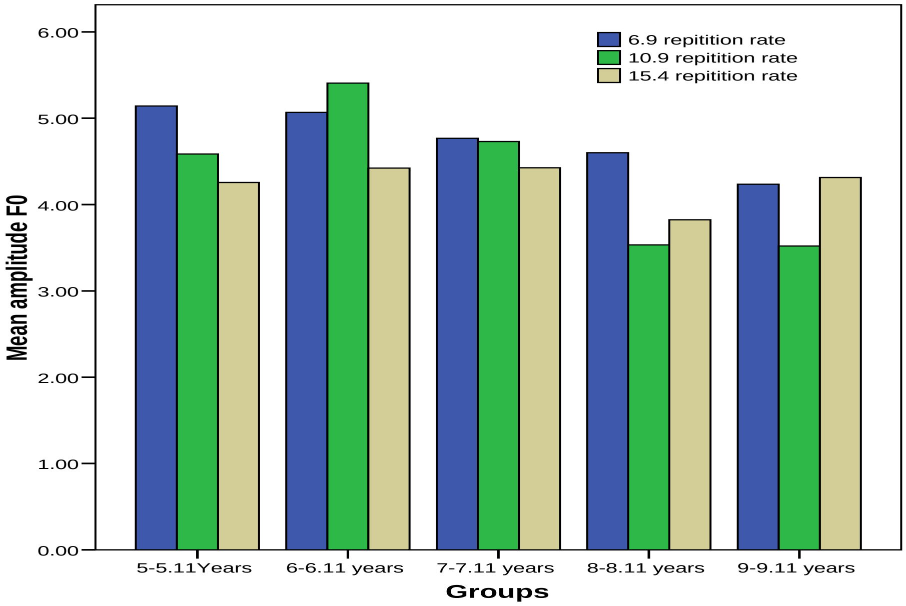

Figure 4.10. Amplitude of F0 at 6.9, 10.9 and 15.4 repetition rates across the groups

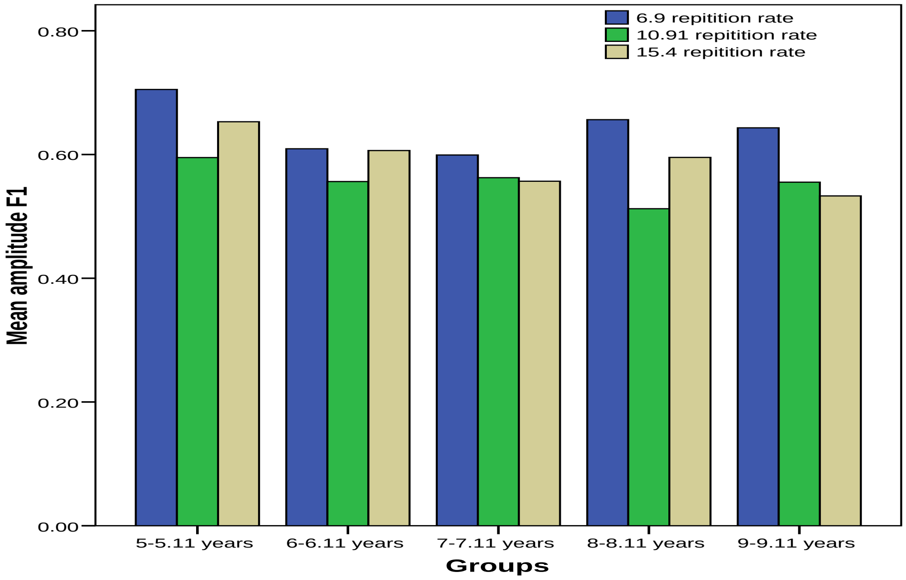

Figure 4.11. Amplitude of F1 at 6.9, 10.9 and 15.4 repetition rates across the groups

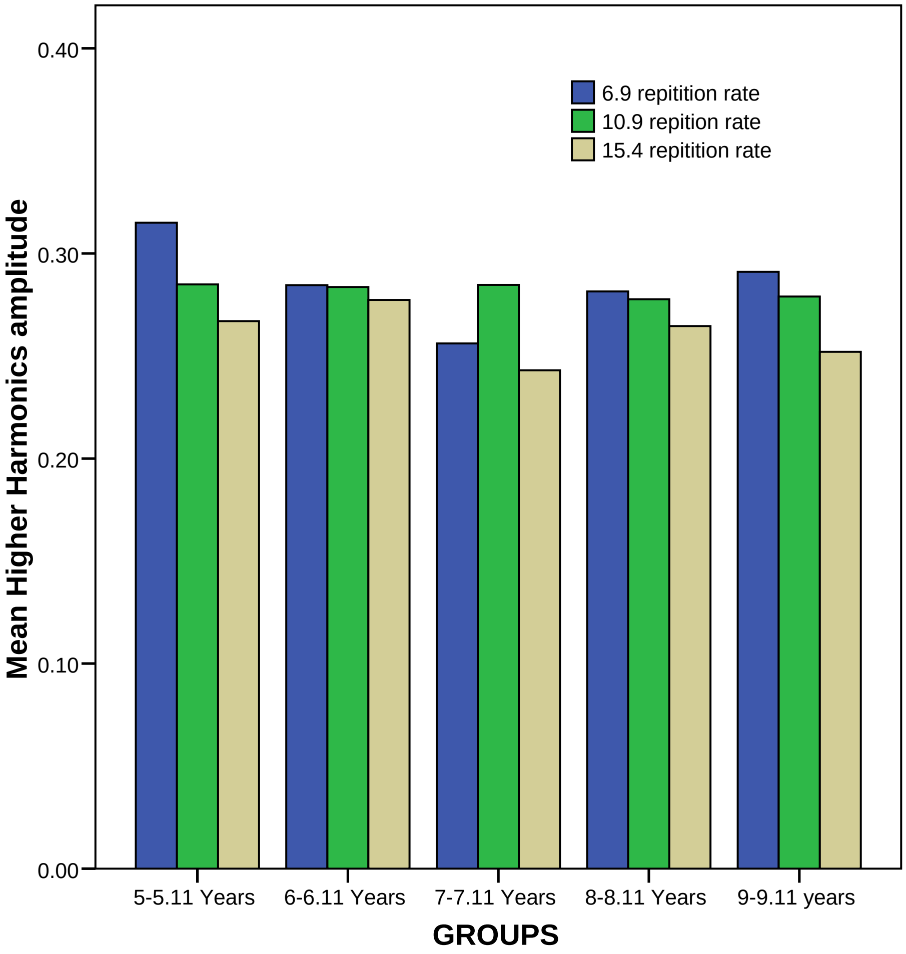

Figure 4.12. Amplitude of Higher harmonics (F2) at 6.9, 10.9 and 15.4 repetition rates across the groups

Table 4.30

Mean and Standard deviations (S.D) of F0, F1 and higher harmonics (F2) amplitude elicited by syllable /da/ obtained at three repetition rates across the group

Peak	Age → Groups	5-5.11 years		6-6.11 years		7-7.11years		8-8.11years		9-9.11 years	
	Repetition rates ↓	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
F0	6.9	5.14	1.94	5.06	2.11	4.76	2.33	4.60	2.12	4.23	1.80
	10.9	4.58	1.37	5.40	2.03	4.73	2.23	3.53	1.66	3.51	1.05
	15.4	4.25	1.85	4.42	2.24	4.42	2.09	3.82	2.06	4.31	1.76
F1	6.9	0.70	0.26	0.60	0.28	0.59	0.21	0.65	0.28	0.64	0.22
	10.9	0.59	0.20	0.55	0.19	0.56	0.13	0.51	0.18	0.55	0.18
	15.4	0.65	0.20	0.60	0.20	0.55	0.16	0.59	0.24	0.53	0.15
F2	6.9	0.31	0.84	0.28	0.08	0.25	0.05	0.28	0.07	0.29	0.06
	10.9	0.28	0.07	0.28	0.07	0.28	0.08	0.27	0.08	0.27	0.07
	15.4	0.26	0.07	0.27	0.10	0.24	0.60	0.26	0.07	0.25	0.06

The mean and the standard deviations of the F0, F1 and higher harmonics amplitude were calculated for the speech evoked FFR recorded at three repetition rates. The mean and standard deviation values obtained are given in table 4.30. It can be seen from the table 4.30 that, as the repetition rate increased, there is a decrease in amplitude of the F0, F1 and also higher harmonics (F2) of speech evoked FFR.

To see the effect of repetition rates and age on F0, F1 and higher harmonics amplitude, Mixed ANOVA (3 repetition rates and 5 groups) was done. The results for each parameter are given below.

Amplitude of FO: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 1.05, p>0.05] groups and repetition rates [F (8, 104) = 0.61, p>0.05] and also across the repetition rates [F (2, 104) = 1.50, p> 0.05]. Thus, further statistical analysis was not done.

Amplitude of F1: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.31, p>0.05] and also groups and repetition rates [F (8, 104) = 0.51, p>0.05]. However, a significant interaction across the repetition rates [F (2, 104) = 5.37, p< 0.05] was observed. As the Mixed ANOVA showed significant interaction across the repetition rates, Bonferroni post hoc test was done to see which two repetition rates for wave F1 amplitude differ significantly from each other. Details of the Bonferroni post hoc test results is shown in table 4.31.

Table 4.31

Bonferroni Post Hoc Test results for the F1 amplitude elicited by syllable /da/ across the three repetition rates

Repetition rate	10.9	15.4
6.9	Significant p<0.05	No Significant p>0.05
10.9		No Significant p>0.05

As the Mixed ANOVA showed significant interaction across the repetition rates taking data from all the group, repeated measure ANOVA (3 repetition rates) was done within the group to see, which group had significant difference in wave F1 amplitude across the repetition rates. Repeated-measures analysis of variance (ANOVA) test results showed that there is no significant difference across the three repetition rates for group I [$F (2, 18) = 1.00$, $p>0.05$], group II [$F (2, 20) = 0.59$, $p>0.05$], group III [$F (2, 24) = 0.61$, $p>0.05$] and also group V [$F (2, 20) = 1.45$, $p>0.05$].

However, a significant difference across the three repetition rates for group IV [$F (2, 24) = 3.57$, $p<0.05$] was noticed. Bonferroni post hoc test was done to see between which two repetition rates wave F1 amplitude, differed significantly for group IV. Details of the Bonferroni post hoc test is shown in table 4.32.

Table 4.32

Bonferroni Post Hoc Test results for F1 amplitude elicited by syllable /da/ across the three repetition rates for group IV

Repetition rate	10.9	15.4
6.9	No Significant $p>0.05$	No Significant $p>0.05$
10.9		No Significant $p>0.05$

A paired t-test was done as Boneferoni post hoc test did not show any significant difference, though repeated measures ANOVA showed significant difference. A paired t-test results showed significant difference between F1 amplitude obtained at 6.9 and 10.9 [$t (12) = 2.63$, $p<0.05$] repetition rates. However, it did not show any significant difference between

6.9 and 15.4 [t (12) = 1.07, $p<0.05$], and also between 10.9 and 15.4 [t (12) = 1.64, $p>0.05$] repetition rates.

Amplitude of Higher Harmonics: The results of the Mixed ANOVA did not show any significant interaction across the groups [F (4, 52) = 0.35, $p>0.05$] groups and repetition rates [F (8, 104) = 0.50, $p>0.05$] and also across the repetition rates [F (2, 104) = 2.84, $p> 0.05$]. Thus, further statistical analysis was not done.

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

1. Repetition rate did not show significant difference on the latency of wave V of click evoked ABR. However, it showed significant difference on the latency of wave V and A of speech evoked transient response and wave D, E and F of FFR.
2. Repetition rate did not show significant difference on the amplitude of wave V of click evoked ABR, wave A of speech evoked transient response, wave D of FFR, F0 and Higher harmonics (F2), however it showed significant difference on the amplitude of wave V of speech evoked transient response, wave E and F of FFR and F1.
3. Age has no significant effect on latency and amplitude of all the parameters considered for the study.

Chapter-5

Discussion

The present study was conducted with an aim of studying the brainstem correlates of the auditory temporal processing in children with different age groups. 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 click evoked ABR

In the present study repetition rate did not show significant affect on the timing of the onset portion of the click evoked ABR, except for IV group.

Present study supports the study by Fowler & Noffsinger, (1983), where they reported no change in latency of click evoked ABR waves with increase in repetition rate between 2-20 Hz. Krizman, Skoe and Kraus (2010) also reported no change in latency of click evoked ABR with increase in repetition rate. However there are studies which reports that there will be prolonged in latency with increase in repetition rate with the previous studies done in adults by Don et al, (1977), Yagi & Kaga, (1979), Lasky, (1984,1997), Burkard & Hecox, (1983, 1987a, 1987b), Thornton & Coleman, (1975) as well as in children by Lasky, (1984, 1997). Basu, Krishnan and Fox (2010) also observed longer latency of click evoked ABR components with the increase repetition rate in children with specific language impairment and children with Normal language.

The difference in the results of the present study could be due to the methodological differences in recording of the click evoked ABR. In the present study the protocol which was used was identical to the reported by Krizman et al (2010). Thus, the present study is in consonance with the earlier studies (Fowler & Noffsinger, 1983; Hall 1992; Hood, 1998; Krizman et al.2010). Thus, it supports the earlier findings that repetition rate to 20/sec may not affect the latency of the click evoked ABR.

Thus, there was no significant effect of repetition rate on the latency of click evoked ABR due to above mentions cause in the present study.

No significant difference in the latency of click evoked ABR across the groups. Salamy (1984) reported that latency of click evoked ABR mature like as adult by the age of 2 years. Gorga et. al. (1989) reported that children by the age of 3 years the latency of click evoked ABR will be same as adult. Johnson et al. (2008) reported that there was no difference in the latency of click evoked ABR for younger children (3-5years) and older children (5-12 years).

As the central auditory process mature by the age of 18 months, no changes can be seen in the latency of click evoked ABR in adults and children (Gorga et al. 1989). Thus, there was no difference seen on the latency of click evoked ABR across group of children as in the current study all the subjects were 5 or above 5 years of age.

Effect of repetition rate on amplitude of click evoked ABR

Repetition rate did not show significant effect on the amplitude of click evoked ABR within the group of children. However, most of the groups showed slight decrease in amplitude with increase repetition rates.

Basu, Krishnan and Fox (2010) reported a decrease in amplitude of wave V with an increase in the repetition rates for all the components for children with specific language impairment and also the normal children. Pratt and Sohmer (1976) also observed similar effect on amplitude with increase in repetition rate. Noffsinger (1983) did not observe any change in the amplitude of click evoked ABR with the increase in repetition rate between 2-20 Hz. However, The rate-related decrease in response amplitude observed for the ABR components may reflect an intensification of neural adaptation (producing a decrease in neural responsiveness) and ⁄or reduced neural synchrony(rate-induced neural desynchronization) in the responding neural elements (Don et al., 1977; Fowler & Noffsinger, 1983; Burkard et al., 1990; Lasky, Shi & Hecox, 1994).

Thus, there was no significant effect of repetition rate on the amplitude of click evoked ABR due to above mentions cause in the present study.

No significant difference seen in the amplitude of click evoked ABR across the groups. Salamy (1984) reported that click evoked ABR mature like adult by the age of 2 years. Jiang, Wu and Zhang (1991) reported that there need not be any age effect on the amplitude of click evoked ABR with increase in rate in children (1-6 years) and Adults (22-36 years). Thus, there was no difference seen in the amplitude of click evoked ABR across group of children as in the current study all the subjects were 5 or above 5 years of age.

Effect of repetition rate on latency of transient response of speech evoked ABR

A significant affect was also noticed for the speech evoked transient response latency (wave V & A). The latency of onset response was increased with an increase in the repetition rates for all the five groups of children, Krizman, Skoe and Kraus (2010) reported that rate affected the timing of the onset of the speech-ABR in adults. Goncalves (2011) reported that longer latency was seen for wave V and A of speech evoked ABR in children with phonological disorders compare to normal children with age range of 7- 11 years. Wible, Nicol and Kraus (2004) also reported that onset of the speech sound /da/, wave V–A of the auditory brainstem response (ABR) had a significantly shallower slope in learning impaired children.

Transient response of speech evoked ABR could be important component in evaluating children who are at risk of developing auditory problems. Change in the latency with increasing rate noticed in children (Lasky, 1984, 1997; Jiang, Brozi & Wilkinson, 1998) could suggests a closer relationship between brainstem neural maturity and rate effects. Delayed neural transmission due to incomplete myelinization and reduced synaptic efficiency is generally thought to produce greater latency changes with rate in infants and children (Pratt & Sohmer, 1976; Lasky 1984, 1997; Jiang et al., 1998).

There was significant effect of repetition rate on the latency of transient response of speech evoked ABR due to above mentions cause in the present study.

No significant difference seen in the latency of transient response of speech evoked ABR across the groups. Johnson et al; (2008) reported that development time course of speech encoding in the brainstem of neural maturation occur at the age of 5 years. Hall and Grose (1994) reported that peripheral mechanism responsible for encoding temporal aspects of the acoustic signal appeared to be well developed in young listeners (4-5years). Thus, there was no difference seen on latency of speech evoked ABR across the groups of children as in the current study all the subjects were 5 or above 5 years of age.

Effect of repetition rate on amplitude of transient response of speech evoked ABR

No significant effect of repetition rate on the amplitude of transient response of speech evoked ABR was seen in the current study. However, there was decrease in Wave V amplitude with the increase in the repetition rate for I, IV and V group except for II and III group. Goncalves (2011) also reported decrease in the amplitude wave V of speech evoked ABR with increase in repetition rate. The decrease in the amplitude of speech evoked ABR with increase in the repetition rates as Goncalves (2011) reported that these responses represent different building blocks of the message, which have different encoding demands.

There was no significant effect of repetition rate on the amplitude of transient response of speech evoked ABR due to above mentions cause in the present study.

No difference seen in the amplitude of transient response of speech evoked ABR across the groups. A similar result was also reported by Goncalves (2011) that there were no significant differences in wave V & A between the groups with age range of 7-11 years. Johnson et al; (2008) reported that development time course of speech encoding in the brainstem of neural maturation occur at the age of 5 years. Hall and Grose (1994) reported that peripheral mechanism responsible for encoding temporal aspects of the acoustic signal appeared to be well developed in young listeners (4-5years). Thus, there was no difference seen in the amplitude of speech evoked ABR across the age group of children as in the current study all the subjects were 5 or above 5 years of age.

Effect of repetition rate on latency of speech evoked frequency following responses

A significant difference was seen in the latency of the peaks D, E, F with increase in rate in all the age groups except wave E latency for V group. Krizman, Skoe and Kraus

(2010) reported that repetition rate had little effect on sustained responses of the speech evoked FFR response. There are studies which reported that the two components of the speech evoked ABR (transient and sustained response) may be generated from two different mechanisms (King et al. 2002; Kraus & Nicole, 2005; Johnson et al. 2005). There are studies which reported that the children with learning problem may have the problem in the onset responses whereas the sustained responses may be normal (Wible, Nicol & Kraus, 2002; Song, Banai, Russo & Kraus, 2006).

There was significant effect of repetition rate on the latency of speech evoked FFR due to due to above mentions cause in the present study.

No significant difference seen in the latency of speech evoked FFR across the groups. This could be the due to observation made by Johnson et al (2008) and Hall and Grose (1994) as explained earlier.

Effect of repetition rate on amplitude of speech evoked FFR

Repetition rate also showed significant effect on the amplitude of the E and F peaks but did not showed significant effect on peak D amplitude. Further, the amplitude of peak E was significant for all the groups except for the IV group, whereas, the amplitude of wave F was significant for I, II, IV group and no significant for III & V group.

Basu, Krishnan and Fox (2010) reported that with an increase in repetition rate there was a decrease in FFR amplitude in normal language development 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. Repetition rate affect did not have much effect on amplitude of speech evoked FFR.

There was significant effect of repetition rate on the amplitude of speech evoked FFR due to above mentions cause in the present study.

However, no significant difference seen in the amplitude of speech evoked FFR across the groups. Again it could be explain by the neural maturation which complete by the age of 5 years (Johnson wt al, 2008 and Hall & Grose, 1994).

Effect of repetition rate on representation of fundamental frequency, first formant and higher harmonics (F2)

No significant difference seen in the amplitude of F0 and higher harmonics (F2) across repetition rate within age group, where as F1 show significant difference across repetition for IV group, but no significant difference seen for group I, II, III and also V. Wible et al. (2004) reported that amplitude of the FFR was significantly reduced among Language learning disability children in the frequency region of first formant (F1) evoked by /da/ stimulus. Krizman, Skoe and Kraus (2010) also reported a similar finding in adult population. There are a lot of studies which support the existence of separate neural mechanisms for the onset response and FFR (Akhoun et al., 2008; Chandrasekaran & Kraus, 2010; Hoormann et al., 1992; Hornickel et al., 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. Background noise is also known to diminish the onset response while the FFR continues to be robust (Russo et al., 2004).

There was no significant effect of repetition rate on the amplitude of fundamental frequency, first formant and higher harmonics (F2) due to above mentions cause in the present study.

No significant difference in the amplitude of F0, F1 and higher harmonics (F2) across the groups. This is mainly due to the age at around 5 years where maturation of auditory nervous system takes place (Johnson et al, 2008, Hall & Grose 1994).

Chapter-6

Summary and Conclusion

Perception of acoustic signals depends on accurate neural 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). 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, the effects of neural fatigue and desynchronization become increasingly evident, helping to reveal minute differences in how temporal cues are processed in various subpopulations (Krizman, Skoe & Kraus, 2010). Brainstem response to speech can be of two type's onset response and the frequency following response which acts as a measure of both spectral and periodicity encoding. 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 children.

To accomplish the aim a total of 57 children have taken for the study. They were further divided in Group I (5years to 5 years 11 months) with 10 ears, Group II (6 years to 6 years 11 months) with 11 ears, Group III (years to 7 years 11 months) with 13 ears, Group IV (8 years to 8 years 11months) with 13 ears and Group V (9 years to 9 years 11 months) with 10 ears having normal hearing thresholds also to observe developmental changes along with the rate effect.

The subjects were prepared using conventional procedure to record auditory brainstem responses. The brainstem response to click stimulus was recorded presented at 80 dB SPL across three repetition rates (6.9, 10.9 & 15.4). The brainstem response to speech evoked ABR was also recorded by using syllable /da/, which was developed by Kraus and colleagues (2002). The syllable was presented at 80 dB SPL across three repetition rates (6.9, 10.9 & 15.4). The speech ABR waveforms contained both the onset (amplitude and latency of peaks V and A) and the sustained (amplitude and latencies of peaks – D, E, F) responses. Fast Fourier Transforms were done to find the raw amplitude of FO, F1 and higher harmonics (F2) frequency components elicited by syllable /da/ using custom made program run on a MATLAB platform. The mean and 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 groups and also within the group of children.

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 five groups and three repetition rates. Repeated measure ANOVA was done within the group to see 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 obtain in current study can be summarized as follows:

- Repetition rates had no significant effect on click evoked wave V latency for each groups and also across groups.
- Amplitude of click evoked wave V did not differed significantly across rate for each groups and also across groups.

- Repetition rate showed significant increase in wave V and A latency evoked by syllable /da/ for all the groups but failed to show any significant difference across group.
- Amplitude of speech evoked wave V showed significant difference across repetition rate for all the groups, but no significant difference was noticed across groups.
- Repetition rate showed significant increase in wave D, E and F latency of sustained response for all the groups but failed to show any significant difference across groups.
- Amplitude of sustained responses did not show any significant difference across repetition rate for all the groups and also across groups.
- Amplitude of F0, F1 and higher harmonics (F2) did not show any significant difference across repetition rate and also across group, except F1 amplitude in group IV.

It can be seen from the above results that latency of occurrence of each wave increased significantly with the increase in repetition rate for the speech evoked ABR, whereas it did not show any effect on click evoked ABR. This could be due to the fact that higher repetition rate cause 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, however, no significant effect of age was noticed for any parameter of the click and speech evoked ABR and FFR. The lack of difference across age could be due to maturation of the auditory brainstem responses which matures by 2 years of age.

The following conclusions can be made from this study:

- It can be concluded from the study that rate has significant affect on processing of speech evoked ABR and FFR.
- Transient component are more susceptible to change with rate but sustained responses may not show significant changes. This suggests that to assess the temporal processing of non-speech and speech stimulus with rate, one must consider transient response rather than sustained response evoked by speech stimulus.
- The current study also suggest that neural processing of temporal aspect of speech stabilizes before 5 years of age as age did not show any significant changes on any wave latency and amplitude of click evoked ABR, speech evoked transient response and FFR and amplitude of F0, F1 and higher harmonics(F2).

Implications of the study:

- Data obtained from the study can be useful as reference to study clinical population.
- The result obtained helped to understand how temporal aspects of non-speech and speech are processed at the nervous system at different repetition rates.
- It gives an idea about the parameters to be considered for further study (transient response) where repetition rates are used to assess temporal processing.
- It highlights the necessity of further study in clinical population.

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