EFFECT OF HEARING-AID-PROCESSED SPEECH ON BRAINSTEM RESPONSES

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ALL INDIA INSTITUTE OF SPEECH AND HEARING

MANASAGANGOTHRI, MYSORE - 570006

June - 2011

Dedicated to my Family, Friends

and Guide

CERTIFICATE

This is to certify that this dissertation entitled "***Effect of Hearing Aid Processed Speech on Brainstem Responses***" is a bonafide work submitted in part of fulfilment for the degree of Master of Science (Audiology) of the student Registration No.: 09AUD022. 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 diploma or degree.

Mysore
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CERTIFICATE

This is to certify that this dissertation entitled "***Effect of Hearing Aid Processed Speech on Brainstem Responses"*** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to 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 hearing aid processed speech on brainstem responses***" is the result of my own study under the guidance of **Dr. Sandeep M.**, Reader in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other university for the award of any diploma or degree.

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June, 2011

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Hearing aids can be classified into analog and digital hearing aids (Sandlin, 2000). Although both types of hearing aids (Analog & Digital) enhance speech perception in individuals with conductive hearing loss, their ability to enhance speech perception in individuals with sensorineural hearing loss has not been satisfactory (Dillon, 2001). This is because of the fact that individuals with sensorineural hearing loss, in addition to their reduced sensitivity, present deficits in temporal resolution (Rawool, 2006), spectral resolution (Turner, Chi, Ling & Flock, 1999), speech perception in noise (Dubno, Dirks, & Morgan, 1984; Helfer & Wilber, 1990 and Suter, 1985) reduced ability to perceive high frequency formant as well as a reduced phase locking (Miller, Schilling, Franck, & Young, 1997). Any device that is provided to enhance speech perception must address these issues for a successful hearing aid fitting. An ideal hearing aid is expected to have an output that is an exact replica of the input speech in terms of its spectral and temporal parameters. On the contrary, electroacoustic measures of hearing aids show a permissible percentage of distortion up to 10 % (Nielsen, Nielsen, & Parving, 1990).

The difference between the output and input speech signals, termed as distortion, could be either in terms of spectral parameters like formant frequencies, formant transition, spectrum of the onset burst etc., or in terms of temporal parameters like VOT, burst duration, transition duration, vowel duration etc. Although the percentage of distortion is correlated well with the extent of reduction in speech perception (Dempsey, 1997), the type of distortion (spectral and temporal) should also be a primary determining factor in the reduction of speech perception. Characterization of distortions introduced by the hearing aid hence becomes necessary. Digital hearing aids have been reported to approximate natural signal more compared to analog hearing aids (Wood & Lutman, 2004), which support a lesser signal distortion in digital hearing aids. Hence, it is also necessary to characterize the distortion separately for analog and digital hearing aids.

The primary purpose of the study is to characterize the distortion induced in analog and digital hearing aids in terms of their spectral and temporal parameters. The secondary purpose is to investigate the effects of such distortion on the signal processing in the auditory brainstem of subjects with normal hearing sensitivity and those with sensorineural hearing loss. Because brainstem responses elicited by speech are reported to evidence even the subtle changes in the signals (Tremblay, Billings, Friesen & Souza, 2003), the present study will adopt auditory brainstem responses to speech as a tool to study the effects of signal processing of speech on the neurophysiology.

1.1 Justification for the Study

It is well established that a hearing aid introduces distortions into the speech output (Licklider, 1946). However, the percentage of distortion introduced by both the types of hearing aids (analog and digital) is not similar (Dillon, 2001). Hence, it is warranted to examine the acoustic properties of the output, from both the types of hearing aids, before it is used for any further investigations.

Individuals with sensorineural hearing loss are known to have inherent deficit in spectral and temporal processing due to the damage of sensory hairs cells. In such situation, the negative influence of hearing aid induced distortions is expected to be more. However, none of the earlier studies documented such effects.

Further it is also important to know that what kind of influence such distortions are going to have on the brainstem signal processing. The majority of studies that have tried to measure the hearing aid benefit using the electrophysiological measures have used long latency response (cortical auditory evoked potential) and revealed confounding findings. Billings, Tremblay, Souza, and Binns, (2007) recorded cortical evoked potentials in normal’s and found that there was no significant effect of amplification on latencies or amplitudes. Korczak, Kurtzberg, Stapells (2005) also studied the benefits of personal hearing aids on subjects with sensorineural hearing loss through cortical ERPs. They found that cortical ERPs were dependent on the degree of sensorineural loss, the intensity of the stimuli, and the level of cortical auditory processing that the response measure is assessing.

1.2 Objectives of the study

1) To compare the spectral and temporal characteristics of speech, before and after it is processed though the hearing aids.
2) To compare the brainstem potentials recorded for processed stimulus with that of unprocessed stimulus in individuals with normal hearing.
3) To compare the brainstem potentials recorded for processed stimulus with that of unprocessed stimulus in individuals with sensorineural hearing loss.
4) To compare processing of unprocessed stimulus and hearing aid processed stimulus at brainstem level between individual with normal hearing and individual with sensorineural hearing loss.

CHAPTER II

REVIEW OF LITERATURE

2.1 Analog Versus Digital Hearing Aid

In addition to the difference in technology, there are several differences between digital and analog hearing aids. Digital hearing instruments provide additional advantages over analog signal processors in the form of greater reliability over time, the robustness of binary code, decreased circuit noise, and greater fitting flexibility because of the ability to program the digital instrument to fit steep or unusual hearing loss patterns (Schweitzer, 1998; Preves, 1995). Hearing instruments with true digital signal processing have features that are not available in hearing instruments with analog signal processing. Analog and digital hearing instruments may provide linear amplification with peak clipping, linear amplification with compression limiting, or wide dynamic range compression (WDRC).

Several studies have compared new digital hearing aids to analog hearing aids currently owned and used by the subjects (Arlinger, Billermark, Oberg, & Lunner 1998; Valente, Bentler, Seewald, Trine, & Vliet 1998). Results of the Arlinger et al's (1998) study indicated a small objective advantage and a strong subjective preference for the digital hearing instrument. Valente, Bentler, Seewald, Trine, & Vliet (1998) found no significant objective difference. These studies may have been influenced by circuitry differences between the digital test instruments, which utilized compression technology, and the analog reference instruments, which utilized several types of circuitry including linear. Additionally, studies have compared newly fit digital hearing aids to newly fit analog hearing aids (Berninger, Karlsson 1999; Boymans, Dreschler, Schoneveld, Verschuure 1999). Results of the Berninger et al study indicated no significant objective difference, but a subjective preference for the digital hearing aid.

A study by Bille, Jensen, Kjaerbol, Vesterager, Sibelle, & Nielson (1999) compared a selected digital hearing aid to a selected model of analog hearing aid under blinded conditions. In this study, no significant objective differences were found between the digital hearing instrument and the analog hearing instrument. Subjectively also, overall there was no significant differences found between the digital hearing instrument and the analog hearing instrument regarding overall preference or overall satisfaction. The only significant subjective difference found between the digital hearing instrument and the analog hearing instrument was that subjects indicated that traffic noise was convenient or less annoying when using the digital hearing instrument.

According to Lopez (1998) similar performance was indicated for all objective and subjective tasks for both hearing aids (analog and digital) with the exception of better performance in quiet at the 40 dB SPL presentation level with the analog hearing aid for the hearing impaired group. There is no distinct advantage found to utilizing a digital processing strategy.

In a study by Hickson, Dodd and Byrne (1995), no significant consonant perception differences were found between linear and compression amplification in quiet for people with mild to moderate sensorineural hearing loss. Consonant perception in noise was adversely affected by compression because of the increase in the level of the noise in relation to the consonant. These results were obtained with a hearing aid that allowed for the selection of two compression conditions for comparison (compression ratios =1.3 and 1.8). Other researchers (Dreschler, 1988; Dreschler, Eberhardt, Melk, 1984) have reported no difference in speech perception in quiet between linear amplification and compression amplification with ratios up to 5. Sammeth, Tetzeli, and Ochs (1996) reported low and non-significant correlations between consonant- vowel ratio (CVR) and percent correct scores for syllables processed with linear amplification and three different nonlinear hearing aids.

Spectrographic analysis revealed that the high frequency response of both hearing aids (linear and nonlinear) was limited compared to the unprocessed signal. After processing through either hearing aid, F1 was unidentifiable. This occurs because of low frequency roll-off that is typical of the frequency response characteristics of most hearing aids. Low frequency gain always is reduced to avoid the effect of upward spread of masking. At high input level periodic temporal structure associated with the vowel generally was absent after processing by linear hearing aid. But for the non-linear hearing aid some evidence of periodicity remains apparent (Stelmachowicz, Kopun, Mace, Lewis, & Nittrouer, 1995). In linear hearing aid, for stimulus /ʃi/, boundary between aperiodic noise and onset of voicing was always obscured (Van Tasell & Trine, 1996).

For the listener with normal hearing or individuals with mild to moderate hearing loss, multiple acoustic cues and linguistic competence may render these acoustic changes irrelevant because as long as majority of speech spectrum is audible, changes in relative frequency response do not produce significant changes in performance (Sullivan, Levitt, Hwang, & Hennessey 1988, Horwitz, Turner, & Fabry, 1991). But previous studies using listeners with hearing loss have shown that audibility alone is insufficient to account for performance (Turner & Robb, 1987; Zeng & Turner, 1990).

In a study done by Garvita and Sandeep (2011) distortions due to hearing aid processed stimuli were characterized. Purpose of that study was to see the effect of hearing aid processed speech on brainstem response. Acoustic analysis and perceptual analysis showed distortion in natural speech due to hearing aid processing. These distortions were in terms of spectral (F1, F2 & F3) as well as temporal (VOT, burst duration, transition duration, and total duration) aspects of the speech stimulus.

2.2 Speech Perception in Normal-Hearing Individuals

F1 transition can be a cue to determine manner of production and the F2 and F3 transitions may provide cues for determining the place of articulation (Kent & Read, 1992).

The stop burst has unique spectral shape. Halle, Hughes and Radley (1957) reported that bilabials (/b/ & /p/) were associated with primary concentration of energy in low frequencies (500-1500Hz). For the alveolar (/d/ & /t/), either was relatively flat or high frequency concentration of energy (above 4 kHz). The burst spectra of velars (/g/ &/k/) had strong concentrations of energy in the intermediate frequency regions of about (1.5-4 kHz). Therefore, place of articulation is differentiated by the spectrum of stop burst.

Formant transition, especially the second formant transition (F2) between stop and vowel is the cue for place of articulation. Liberman, Delartte, Cooper and Gerstman (1954) studied the effect of varying F2 transition on the identification of place of articulation for voiced stops. Listener identified all the stimuli with the rising F2 transition as bilabial, slightly falling as alveolar and sharply falling as velar stops.

Released burst energy increases as the point of occlusion moves back in the mouth (bilabial ‹ alveolar‹ velar). So burst amplitude could serve as a cue to distinguish alveolar and dental stops (Jongman & Blumstein, 1985).

Closure duration is a cue for place of articulation. Duration of closure decreases as the occlusion moves backward in the oral tract. So closure duration increases from velar to bilabial place of articulation (Repp, 1984).

Peterson and Lehiste (1961) reported that the bilabials usually have shorter initial transition than lingual consonants and it's a cue for perception of different consonants.

Voice onset time (VOT) interact with place of articulation, with shorter VOT values (Peterson & Lehiste, 1960). Bilabials have shorter VOT and velar have lngest VOT.

2.3 Speech Perception in Individuals with Sensorineural Hearing Loss

Turner, Smith, Aldridge and Stewart (1996) studied the perception of /ba/, /da/, & /g/ in CV contrast where they varied the transition duration from 5to 160ms in moderate hearing impaired listeners. They found worse perception in all the places as the transition duration increased. There was inverse relation between degree of hearing loss and sores with increase in transition. Dormann (1985) studied manner of perception for fricative and affricates distinction in Mild to moderate hearing loss individuals and reported that there was mild impairment with the variation of frication duration and mild impairment with a variation of transition duration.

In a study of simulated high frequency hearing loss for distinction among stops, nasal and fricatives, Geetha, Ashly and Ythiraj (2000) found that perception was stops was more affected than nasals and fricatives. And voicing errors were more in sharply sloping than gradual sloping. According to Zeng and Turner (1990) hearing impaired listeners could achieve close to normal speech perception when given equivalent degree of audibility of fricatives but not for transition cue. Revoile, Pickett, Holden & Talkin (1987) studied the effect of VOT in the voicing perception in moderate hearing impaired and they found that VOT was a strong voicing cue for both hearing impaired and normal hearing individuals.

Thus, the speech perception is different in normal hearing and sensorineural hearing loss individuals. It is degraded in individuals with sensorineural hearing loss. The cues used by the 2 groups of individuals are also different.

2.4 Brainstem Responses to Speech Stimulus

An essential function of the central auditory system is the neural encoding of speech sounds. The ability of the brain to translate the acoustic events in the speech signal into meaningful linguistic constructs relies in part on the representation of the acoustic structure of speech by the central nervous system (Abraham & Kraus, 2006).

One of the challenges faced by researchers interested in this subject is that speech is a complex acoustic signal that is rich in both spectral and temporal features (Nusbaum and Morin, 1992).

There are two basic approaches that researchers have adopted for conducting experiments on speech perception and underlying physiology. One approach uses "simple" acoustic stimuli, such as tones and clicks, as a means to control for the complexity of the speech signal. While simple stimuli enable researchers to reduce the acoustics of speech to its most basic elements, because the auditory system is nonlinear (Sachs & Young, 1979; Sachs, Voigt, Young, 1983; Rauschecker, 1997; Nagaraja, Cheung, Bedenbaugh, Beitel, Schreiner, Merzenich, 2002), responses to simple stimuli generally do not accurately predict responses to actual speech sounds. A second approach uses speech and speech-like stimuli (Song, 2006). There are many advantages to this approach. First, these stimuli are more ecologically valid than simple stimuli. Second, a complete description of how the auditory system responds to speech can only be obtained by using speech stimuli, given the nonlinearity of the auditory system. Third, long-term exposure to speech sounds and the subsequent use of these speech sounds in linguistic contexts induces plastic changes in the auditory pathway, which may alter neural representation of speech in a manner that cannot be predicted by simple stimuli. Fourth, when speech stimuli are chosen carefully, the acoustic properties of the signal can still be well controlled.

Physiological Representation of Speech in the Auditory Brainstem

The auditory brainstem codes for the different parameters of speech like the formant structure, periodicity, formant transitions, and acoustic onsets, which are then relayed to the cortical structures to complete the processing of these features.

Table 2.1: *Physiological correlates of the different features of the acoustic speech signal (and their representation through evoked potentials)*

General acoustic features in speech	**Features role in speech signal**
Formant structure	Ubiquitous in vowels, approximants and nasals are essential for vowel perception
Periodicity	Temporal cue for fundamental frequency and low formant frequencies
Frequency transition	Consonants identification, signal the presence of diphthongs and glides, linguistic pitch
Acoustic onset	Phoneme identification

Auditory brainstem responses provide direct information about how the sound structure of a speech syllable is encoded by the auditory system. It is particularly compelling to consider that specific aspects of the sound structure of the acoustic signal are maintained and reflected in the neural code. Similar to the speech syllable itself, the brainstem response to a speech syllable can be divided into transient and sustained portions namely the onset response and the frequency-following response (FFR) (Boston & Moller, 1985). The robust onset response is similar to that observed in response to a tone or click stimulus, consisting of waves I, III, and the VA complex. The voiced portion of the stimulus evokes the periodic portion of the response, the FFR, which reflects phase-locking to the waveform of the stimulus.

Studies have shown that F0 is represented within the steady-state portion of the brainstem response (i.e., FFR) according to a series of negative peaks that are temporally spaced in correspondence to the wavelength of the fundamental frequency.

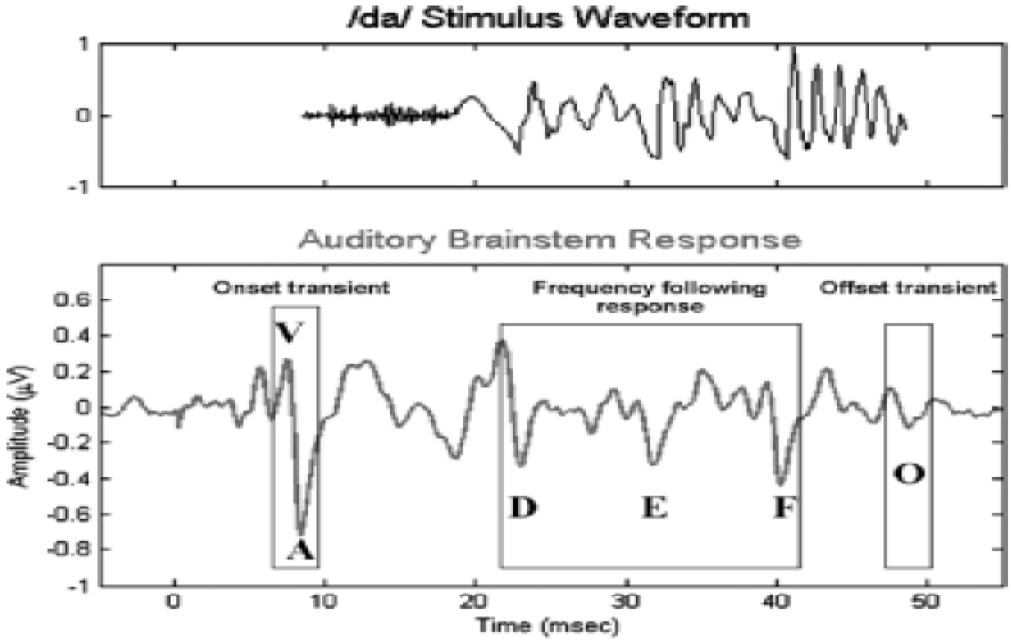

*Figure: 2.1.*Acoustic waveform of the synthesized speech stimulus /da/ (*above*) and grand average auditory brainstem responses to /da/ (*below*).

The stimulus has been moved forward in time to the latency of onset responses (peak V) to enable direct comparisons with brainstem responses. Peaks V and A reflect the onset of the speech sound, and peak O reflects stimulus offset. Peaks D, E, and F represent a phase-locked representation to the fundamental frequency of the speech stimulus, and the peaks between D, E, and F occur at the F1 frequency.

F0 is represented in the FFR, which shows the waveform of the speech stimulus /da/ , The primary periodic features of the speech waveform provided by the F0 are clearly represented in peaks D, E, and F of the FFR brainstem response. Importantly, it has been shown that the FFR is highly sensitive to F0 frequency; this aspect of the brainstem response accurately “tracks” modulations in frequency (Krishnan, Gandour & Cariani, 2004).

Krishnan (2002) studied that at higher stimulus intensities, the brainstem FFR accurately represents F1 and F2; however, the representation of F1 has an increased representation relative to F2. A similar result was found in a classic study of vowel representation in the auditory nerve of anesthetized cat (Sachs and Young, 1979). These data provide evidence that phase-locking serves as a mechanism for encoding critical components of the formant structure in the auditory nerve as well as auditory brainstem.

The short-latency FFR is able to follow, frequency changes in speech. This phenomenon was demonstrated in a study of FFR tracking of the fundamental frequency (F0) in Mandarin speech sounds (Krishnan, Gandour & Cariani, 2004).

In Mandarin, a "tonal" language, many words are differentiated the F0 contour acoustic cue. FFR represented the fundamental frequency modulations for all of the stimulus conditions, irrespective of the form of the frequency contour.

The first components of the speech-evoked ABR reflect the onset of the brainstem response to the stimulus. Speech onset is represented in the brainstem response at approximately 7 ms in the form of two peaks, positive peak V and negative peak A.

Acoustic cues used by individual with hearing impairment are different from those used by individual with normal hearing. Hearing aid is a device that can help in perceiving those missing acoustic cues in individual with hearing impairment. So, goal of hearing aid selection process is to define the appropriate physical and electroacoustic characteristics of the desired hearing aids for a particular individual using method that will facilitates ordering, verification and validation of the devices.

2.5 Objective Measures for Selection of Hearing Aids

Objective measures like auditory evoked potentials are the possible ways of evaluating the effectiveness of the hearing aid in infants or children with development delay or other disabilities.

Auditory brainstem response:

It is useful in evaluating hearing aids' benefit for the processing of speech in individuals with hearing impairment. ABR recording done by clicks or tonebursts may not activate the hearing aid compression circuitry in the same way as longer duration speech sound (Brown, Klein & Snydee,1999), and may be treated as noise by hearing aid (Alcantara, Moore, Kuhnel & Launer, 2003). Speech evoked ABR gives better response than the evoked by clicks or tone-bursts.

Khaladkar, Karthik and Vanaja (2005) evaluated the relationship between speech identification scores (SIS) and ABR measure and cortical responses in individual with sensorineural hearing loss. The results revealed that there is significant relationship between SIS and speech evoked ABR. They concluded that the cochlear hearing loss impairs the processing of burst and the transition portion for the speech evoked ABR. And it was observed that speech evoked ABR was more reliable than the cortical measures.

Middle latency response (MLR):

Like the ABR , Fast rate auditory steady state is not an ideal tool for the objective hearing aids evaluation as it is more affected by subject state (Mc Gee & Kraus, 1996) and is more variable, both within and between subjects than ABR (Dalebout & Royey, 1997).

Auditory Steady State Response (ASSR):

ASSR generated by amplitude modulated sinusoids has been used to measure unaided versus aided hearing thresholds in hearing impaired (Picton, 1998). As it is not affected sleep and sedation and gives frequency specific information. It has been used for paediatric population and non-cooperative subjects. Dimitrijevic, John and Picton (2004) found that the number and amplitudes of ASSR components evoked by independent amplitude and frequency modulation (IAFM) of the tones were related to word recognition scores in adults.

Vanaja and Manjula (2004) studied the benefit of ASSR as an objective method for hearing fitting. They compared aided ASSR and behavioral functional gain, and found a positive correlation between the two measures suggesting that ASSR can be used for hearing fitting.

Cortical auditory evoked potentials (CAEP):

It reflects the functional integrity of the auditory pathway involved in the processing of complex speech stimuli (Ostroff, Martin, & Boothrod, 1998; Tremblay, Friesen, Martin, & Wright, 2003). It can be used to understand the neurophysiological basis of speech perception, which would give information of speech processing abilities of the individual (Tremblay, Friesen, Martin & Wright, 2003). Cortical responses have also been studied to correlate with auditory processing in individuals with learning disabilities and sensory neural hearing loss (Kraus, Mc Gee, Carrell, Zecker, Nicol & Koch, 1996). It is one of the ideal objective tools for aided hearing instrument evaluation because it is reliably present in young infants and adults, it correlate well with the perception. It can be evoked by speech stimuli and seems to be sensitive to differentiate between speech stimuli like voice onset time, place of articulation (Tremblay, Friesen, Martin & Wright, 2003).

CAEP thresholds are routinely used by clinicians to estimate hearing sensitivity in adults because P1-N1-P2 response threshold agree very well with audiometric threshold determined behaviorally (Cody, Klass & Bickford, 1967; Tsu, Wong & Wong, 2002). The most common clinical application of CAEP testing is objective threshold estimation in adults thought to have a non-organic or exaggerated hearing loss (Rieckards & De Vidi, 1995). Cortical evoked potentials are affected by both arousal level and attention and are typically recorded when the person being tested in awake and alert or in a light sleep stage (Cody, Klass & Bickford, 1967).

Thus, different auditory evoked potentials have been used for the selection of hearing aids. However, most of them lack accuracy. Speech evoked brainstem responses (onset and FFR) has been proved to be powerful tool which represents source as well as filter cues of speech. Consonants which contribute primarily to the intelligibility of speech (Kent & Read, 1995), are to be accurately coded in the auditory nervous system. The place and manner of articulation are cued by the source and filter cues. If speech evoked brainstem responses can accurately represent both these cues, then speech processing can be effectively studied. However, there is dearth of literature where brainstem responses are used to understand the hearing-aid processed speech. Hence, the present study was taken up.

CHAPTER III

METHOD

The present study hypothesized that there is no difference in the brain stem responses recorded for hearing aid processed speech compared that to that elicited by original unprocessed stimulus. The study used a true experimental design, standard group comparison design and the following method to test the null hypothesis.

3.1 Subjects

Fifty one subjects participated in the study. They were divided into two groups; a control group having 29 adults with normal hearing sensitivity and clinical group having 22 adults with mild to moderate degree of sensorineural hearing loss. All the subjects taken for the study were in the age range of 18 to 45 years.

Subject Selection Criteria:

Subjects in the Group 1 were required to have three important qualifications. First, they had to have normal hearing (hearing acuity within 15dBHL) at octave frequencies between 250Hz and 8000Hz for air conduction and, between 250Hz and 4000Hz for bone conduction. Pure-tone audiometry was done using a calibrated diagnostic audiometer (Grason Stadler, Inc. SI-61) with TDH 39 supra aural earphones and Radio ear B-71 BC vibrator as transducers.

Second, they had normal middle ear function as assessed on Immittance audiometry using calibrated middle ear analyzer (GSI Tympstar). Only those with type ‘A’- tympanogram with normal ipsilateral and contralateral reflexes were considered for the study. There was no history of relevant otological or neurological dysfunction, and all of them were screened for auditory processing disorder by administrating speech perception in noise (SPIN) test at 0dB SNR. A score of more than 60% was the third qualifying criteria.

On the other hand subjects in Group 2 had mild or moderate degree of sensorineural hearing loss which was either flat or gradually sloping in configuration. They had type-A tympanogram and absent otoacoustic emissions indicative of outer hair cells' dysfunction.

3.2 Test Procedure

The experiment involved 3 phases

Phase 1: Generation of the test stimuli

Phase 2: Perceptual and acoustic analysis of the generated stimuli

Phase 3: Recording of the auditory brainstem responses

3.2.1 Phase 1 - Stimulus Generation

Auditory brainstem responses were recorded by using speech syllable /da/ borrowed from Professor Kraus, Principal Investigator, Auditory neuroscience lab, Northwestern University, Chicogo. The stimulus is 40 ms in duration (generated using Klatt synthesizer) (Klatt, 1980). It comprises of an initial noise burst and formant transition between the consonant and the vowel. It includes an onset burst frication at F3, F4, and F5 during the first 10ms, followed by 30 ms F1 and F2 transitions ceasing immediately before the steady state portion of the vowel. The F0 and the first three formants (F1, F2, & F3) change over the duration of the stimulus: F0 from 103 to 125

Hz, F1 from 220 to 720 Hz, F2 from 1700 to 1240 Hz, and F3 from 2580 to 2500 Hz. F4 and F5 are constant at 3600 and 4500 Hz respectively.

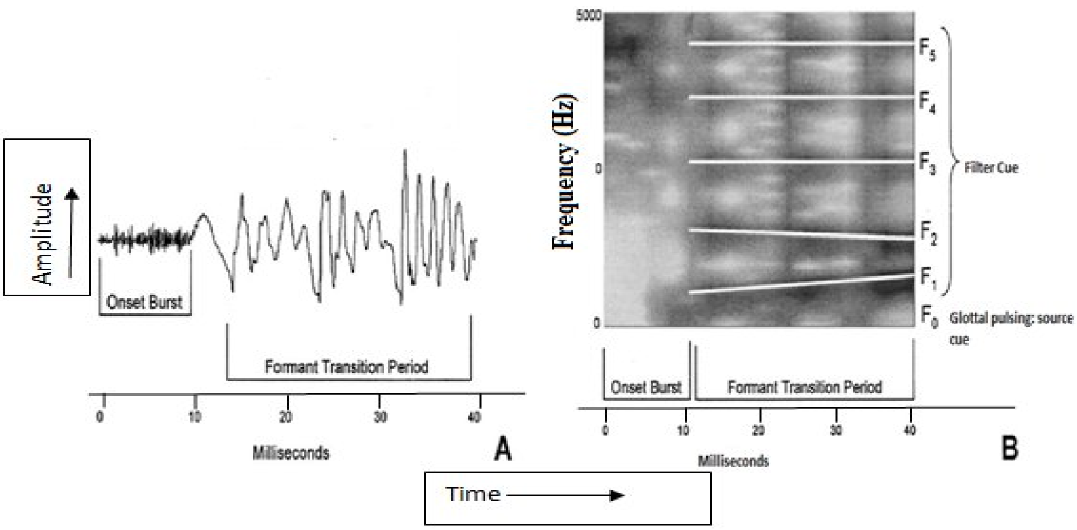

Figure 3.1 (A) Time-amplitude waveform and *(B)* Spectrogram of Synthetic Syllable /da/.

Syllable /da/ was used because of 2 reasons. One, being a stop consonant it consists of evident onset burst and formant transition which can elicit better electrophysiological responses. Second, because of its complex spectral structure, any subtle distortions in the spectrum secondary to signal processing through hearing aid shall be evident. A short duration syllable was preferred, as a longer analysis window (that is necessary to record responses elicited by longer duration stimulus) restricts the repetition rate which in turn prolongs the duration of testing.

To compare the processed and the natural stimulus in phase 2 and phase 3, stimulus /da/ was processed through a digital (DH+ Alps) and an analog (Alps N) hearing aid. Two hearing aids were of same company (Alps international limited).

The characteristics of the hearing aids were matched to maintain the uniformity. Both were moderate gain hearing aids. Analog hearing aid was with a trimmer control while the digital hearing aid was multi channel with WDRC (wide dynamic range compression) and noise reduction algorithm features. However, WDRC and Noise reduction algorithm were switched off to rule out the influence of those features. The EAC (Electroacoustic characteristic) of the 2 hearing aids as measured by Fonix7000 are as given in Table 3.1. The matched output curves of the two hearing aids are shown in figure 3.2.

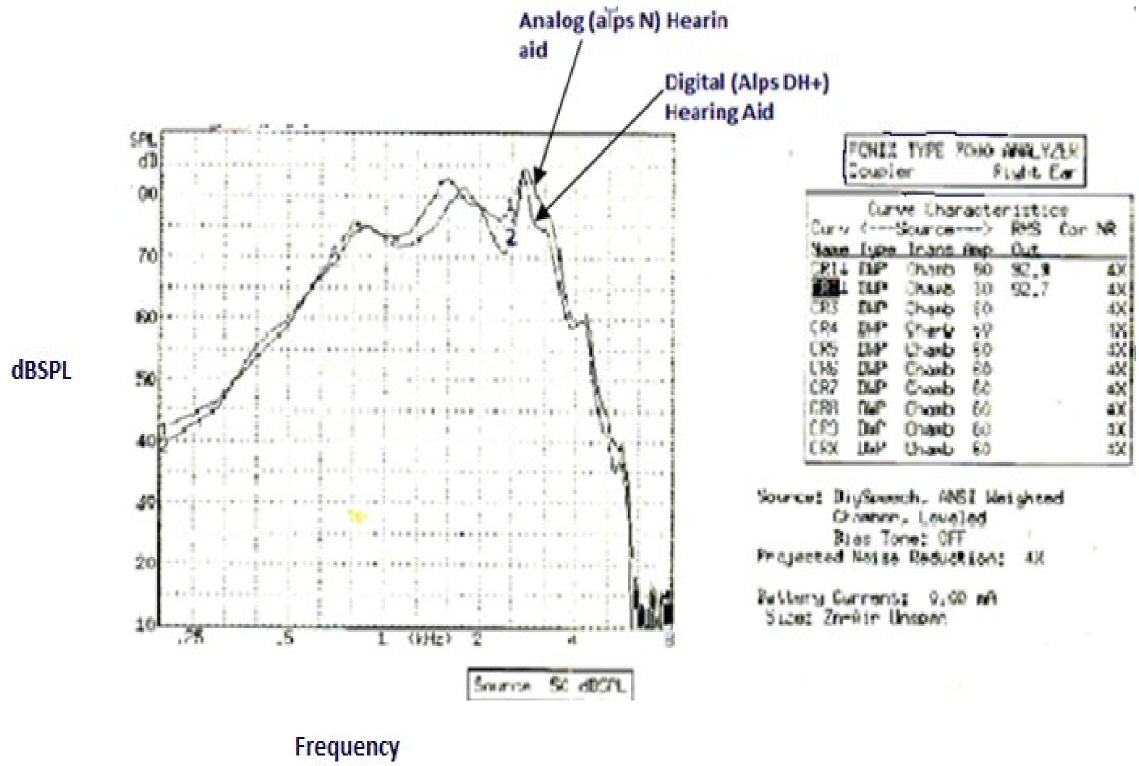

Figure3.2. Matched Output of two hearing aids for the same input level.

Table 3.1*: Electroacoustic Characteristics of two hearing aids*

Measurement Parameter	Hearing Aid	
	Alps N (analog hearing aid)	Alps DH+ (Digital Hearing aid)
OSPL90	1kHz - 119.34dB HFA Level - 116.4 dB	1kHz- 119.5dB HFA Level-116.9dB
Full on gain	HFA level - 44.2dB	HFA Level-44.3dB
Frequency response	200Hz to 4477Hz	200Hz to 5000Hz
Equivalent input noise	17.9dB	9dB
Battery current drain	1.5mA	0.9mA
Harmonic distortion	2.48 %	1.89%

To record the stimulus processed through the hearing aids, stimuli were initially fed into a computer. The audio output of computer was routed into a calibrated diagnostic audiometer. The syllables were then played at 40 dB HL and 45 degree azimuth through the sound field speaker. An analog hearing aid or a programmed digital hearing aid was placed in the subject's position at a 1 meter distance. The receiver of the hearing aid was connected to a 2cc coupler. The other end of the coupler was attached to a Sound Level Meter (SLM). The SLM in turn was connected to another computer which received the processed stimulus. The so recorded stimulus was then normalized to maintain the overall amplitude constant across stimuli. A block diagram of the set up is shown in Figure 3.3.

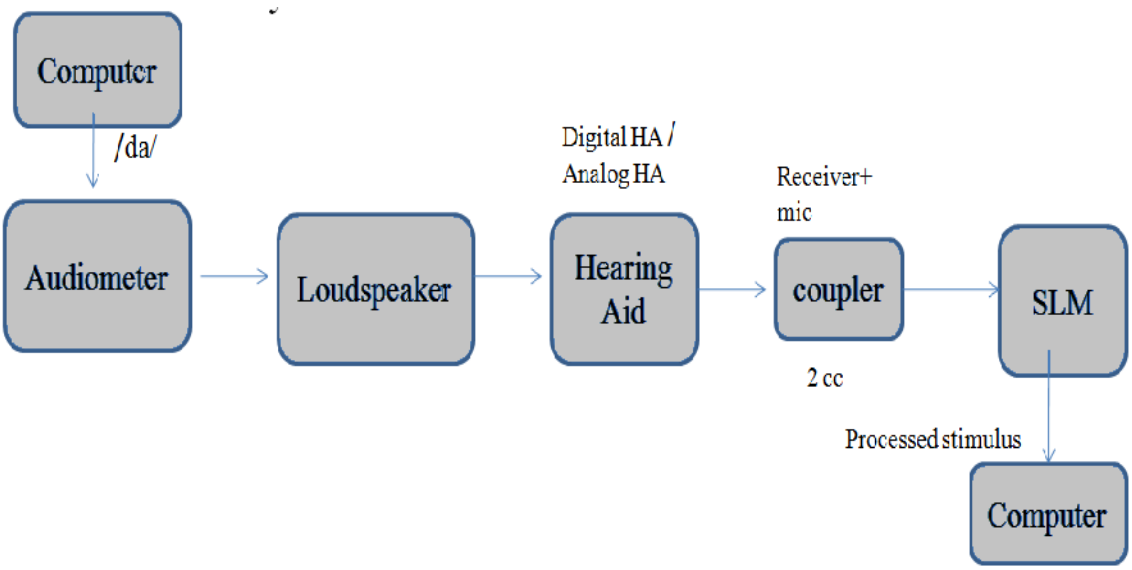

*Figure 3.3.*Block diagram of instrumentation and setup used for recording the processed stimuli.

3.2.2 <u>Phase 2 - Acoustic and Perceptual Analysis of unprocessed and Processed /da/ Syllables</u>

3. 2.2.1 Acoustic Analysis

Spectral and temporal aspects of the unprocessed stimulus and the processed stimuli were studied using PRAAT (version 4.1.21) software. Comparison was made across unprocessed stimulus, stimulus processed through analog hearing aid and stimulus processed through digital hearing aid. The parameters analyzed included Fundamental frequency, F1, F2, F3, F4, total stimulus duration, burst duration, and formant transition duration. The analysis was carried out by speech pathologists, with expertise in acoustic analysis. The spectrograms of the 3 syllables are shown in Figure 3.4(a-c).

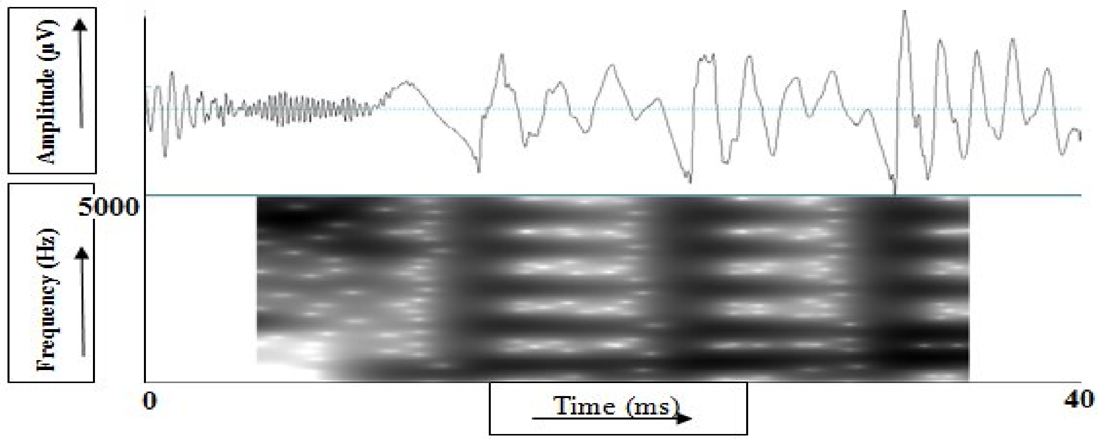

*Figure 3.4(a).*Spectrogram of the unprocessed stimulus /da/.

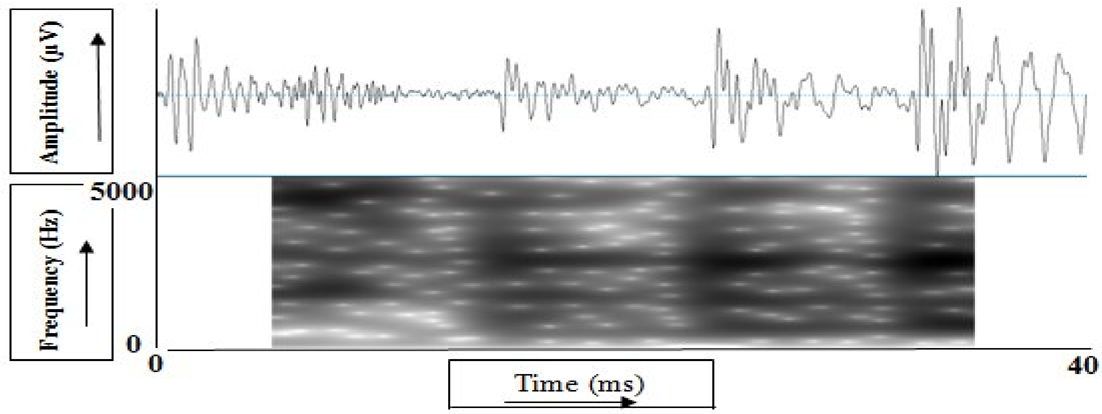

Figure 3.4(b). Spectrogram of Analog hearing aid processed stimulus /da/.

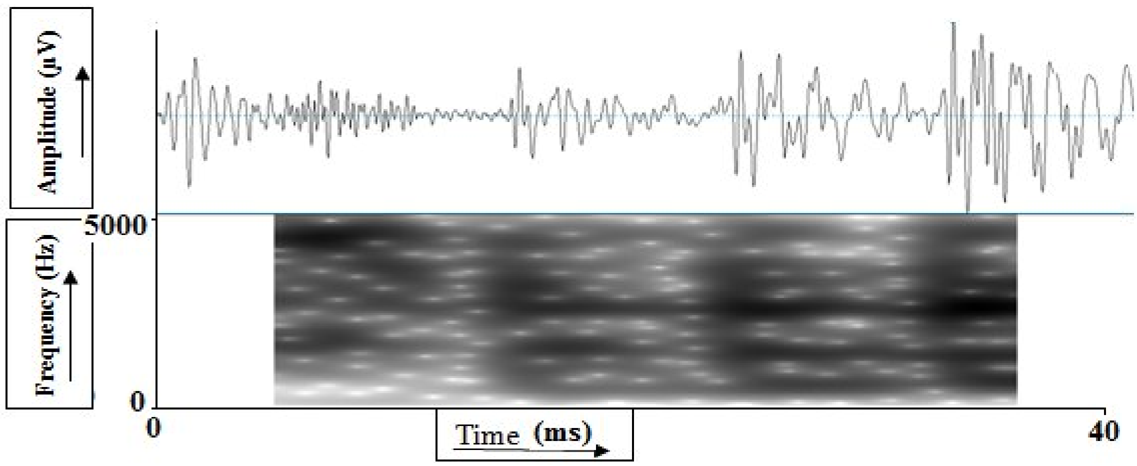

Figure 3.4(c). Spectrogram of digital hearing aid processed stimulus /da/.

3.2.2.2 Perceptual Analysis:

Stimuli were perceptually analyzed for the quality. The three syllables were played to 20 sophisticated listeners at comfortable levels through audioteck. The participants were instructed to rate the naturalness on a five-point rating scale wherein '1' is most natural, '2'- near natural, '3'- moderately natural, '4'- almost unnatural and '5'- completely unnatural.

3.2.3 Phase 3 - Recording of Auditory Brainstem Responses

Auditory brainstem response (ABR) were recorded for the 3 target stimuli in a sound treated room where the noise levels were as per the guidelines in ANSI S 3.1 (1991). The clients were seated comfortably in a reclining chair. The skin surface at the vertex (Cz), nape of the neck, and forehead (Fz) was cleaned with skin abrasive gel, to obtain the absolute electrode impedance of less than 5 kΩ and inter-electrode impedance of less than 2 kΩ. The electrodes were placed with the help of skin conduction paste and secured tightly in their respective places using surgical plaster. Participants were instructed to relax and refrain from extraneous body movements to minimize artifacts. The testing was done monaurally in both the ears. The stimulus and acquisition parameters used for recording brainstem responses are given in Table 3.2.

Table 3.2*: Protocol for recording auditory brainstem responses*

Parameters	**Target Settings**
Stimulus Parameters	
Stimulus	1. /da/- unprocessed 2. Hearing aid processed -/da/-digital hearing aid -/da/ - analog hearing aid
Duration	40 ms
Polarity	Rarefaction
Stimulus Intensity	70 dB nHL
Repetition Rate	7.1Hz
Acquisition Parameters	
Mode	Ipsilateral
Analysis Time	60 ms
Band Pass Filter	30 to 3000Hz
Electrode Montage	Vertical - Fpz, Cz, Nape
Sweeps	1500
Transducer	Insert ER-3A
Electrode Impedance	<5 k Ohms
No. of Channels	One
No. of Replications	Two

3.2.3.1 Response Analysis

Brainstem responses elicited by speech were visually analyzed independently by two experienced audiologists in the area of electrophysiology. Only the replicated waves were considered for the analysis. Both transient and sustained elements of the responses were analyzed. Each individual wave was analyzed to record latency and amplitude of wave V, A, C, D, E, F and O. The marking of the wave in a representative is shown in Figure 3.5.

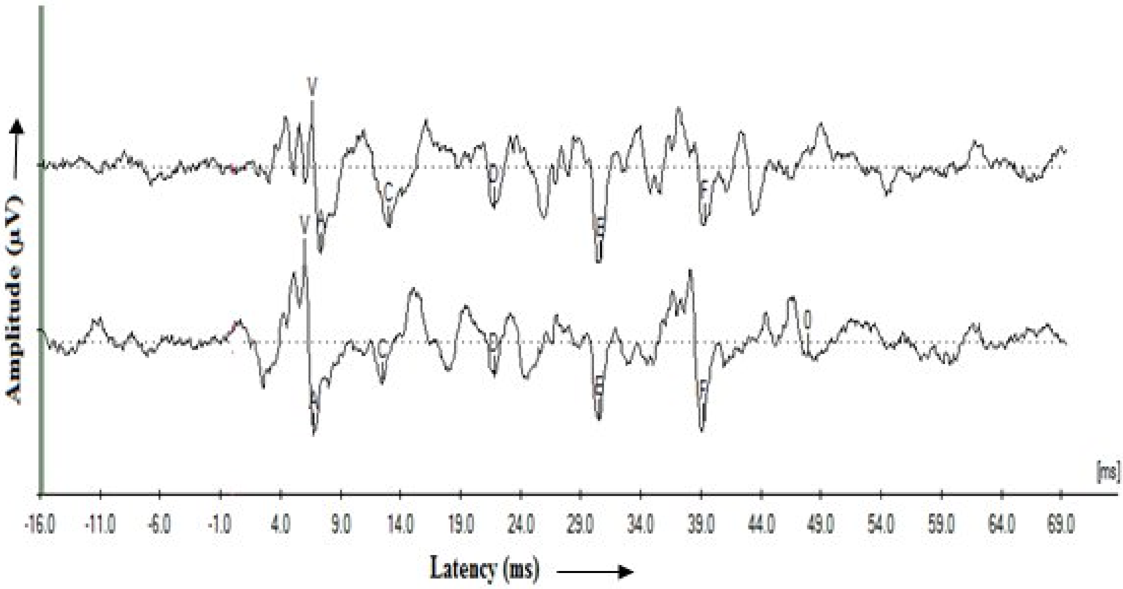

Figure3.5. Brainstem response evoked by syllable /da/, with the peaks marked.

The sustained portion was further analyzed using Fast Fourier Transformation (FFT) to record the energy at frequencies corresponding to F0 and F1. 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 higher harmonics in order to assess the amount of activity occurred at all these three frequencies. To do this, 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, Stainsby, Wright, Wood. 2001; Russo, Nicol, Musacchia & Kraus, 2004). A 2 ms on 2 ms 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, Nicol, Musacchia & Kraus, 2004). This calculation was performed by comparing the spectral magnitude of the pre-stimulus period to that of the response. 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, Nicol, Musacchia & Kraus, 2004). The rms (root mean square) amplitude value of the F0 or F1 frequency and higher frequency component of the response FFR were then measured in arbitrary dB.

3.3 Data Analysis

The data thus obtained was tabulated to obtain Mean and Standard deviation to answer the following questions:

1. Whether the spectral and temporal characteristics of speech change after processing through the hearing aid. If so, is it true with both analog and digital hearing aids?
2. Perceptually, are the original and the hearing aid processed speech different?
3. Are the brainstem elicited by the original synthetic syllable and the hearing aid processed syllables different? If so, in what parameters?
4. Are the brainstem responses elicited in the two groups of target population similar?

CHAPTER IV

RESULTS

The primary aim of the study was to compare the speech processed through hearing aids to that of the input speech to characterize the differences and compare the brainstem responses recorded for these stimuli. The secondary aim of the study was to see whether brainstem responses elicited by these stimuli in individuals with sensorineural hearing loss are different from that of normal hearing individuals. The results of the study are discussed under the following headings:

1. Results of Acoustic Analysis
2. Results of Perceptual Analysis
3. Results of Brainstem Responses

4.1 Results of Acoustic Analysis

Acoustic analysis was carried out on the 3 test stimuli to identify the spectral and temporal parameters, which were then compared for any differences. The spectral and temporal measures of the unprocessed /da/ and the processed /da/s are given in Table 4.1. It was carried out by speech pathologists with experience in the area for more than 5 years. Results of the acoustic analysis revealed that the signal processing influenced spectral as well as temporal parameters of the syllable /da/. For the acoustic analysis, the spectral parameters considered were fundamental frequency and the subsequent higher formants (first, second, third and fourth). Among these parameters, fundamental frequency did not vary between unprocessed /da/ and processed /da/ stimuli, while first, second, third and the fourth formants were different (higher), in processed stimuli compared to that in unprocessed stimulus.

The temporal parameters considered in the spectral analyses were burst duration, transition duration and the overall duration of the stimulus. Among these measures (burst duration & transition duration) marginal differences were seen in burst as well as transition durations. Burst duration was increased while the transition duration was decreased in the processed stimuli compared to the original /da/. There was no considerable difference between temporal measures of stimulus processed through analog and digital hearing aids.

Table 4.1: Spectral and temporal measures of unprocessed stimulus, analog hearing aid-processed stimulus and digital hearing aid-processed stimulus

	Parameters	Unprocessed /da/ Stimulus	Analog hearing aid processed /da/ Stimulus	Digital hearing aid processed /da/ Stimulus
Spectral parameters	F0 (Hz)	116.80	116.11	116.86
	F1 (Hz)	493.45	789.29	758.31
	F2 (Hz)	1467.42	1551.24	1501.80
	F3 (Hz)	2600.01	2520.42	2568.31
	F4 (Hz)	3693.77	3246.87	3335.73
Temporal parameters	Burst duration (ms)	10	12.62	12.73
	Transition duration (ms)	30	25.51	25.72
	Total duration (ms)	40	40	40

4.2 Results of Perceptual Analysis

The 3 stimuli were perceptually rated on a 5-point rating scale. The compilation of the rating of the 3 stimuli by the 20 sophisticated listeners is shown in Figure 4.1. It can be seen in the figure that most of the listeners rated original unprocessed /da/ as either natural, near natural or moderately natural. None of them perceived it to be almost unnatural or completely unnatural. However, this was not the case with processed stimuli. Neither of the processed stimuli was rated most natural by any of the listener. Within the 2 processed stimuli, output of the analog hearing aid was perceptually rated poorer than the digital hearing aid.

To see whether these observed differences in the perceptual rating were statistically significant, ‘Equality of Proportions’ was used. In this, the number of listeners who rated the 3 stimuli as natural were compared. Results showed that the number of individuals who rated the unprocessed stimulus as natural were significantly higher [$Z=4.50$, $p<0.05$] compared to that of processed stimuli. Because the number was ‘zero’ in both analog and digital hearing aids, the same Z-value is applicable for both the processed stimuli. While comparing between the 2 processed stimuli, the rating between most natural, moderately natural, almost unnatural and completely unnatural were not considered as the number of listeners who gave these ratings were same in both the conditions. But when they were compared on ‘near natural rating’, results showed no significant difference [$Z=0.38$, $p>0.05$] between them.

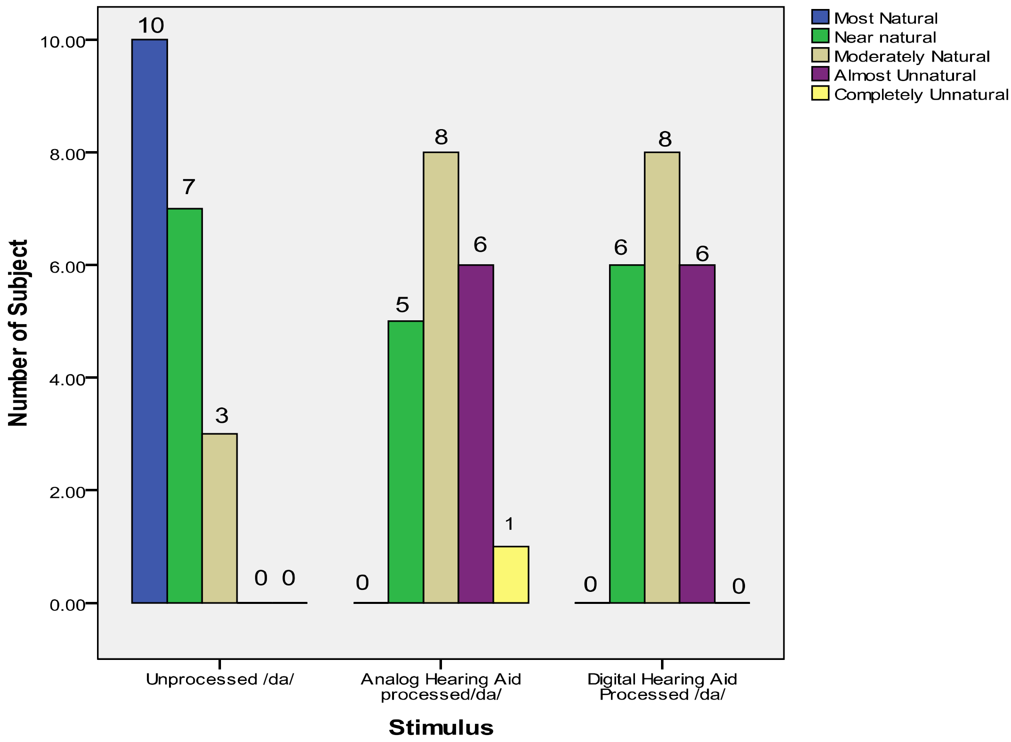

*Figure 4.1.*Perceptual judgment of unprocessed /da/, /da/ processed through digital hearing aid and /da/ processed through analog hearing aid on a five point rating scale by 20 sophisticated listeners.

4.3 Results of Brainstem Responses

4.3.1. Percentage of Occurrence of Waves of Brainstem Response

The latency and amplitude measures of waves V, A, C, D, E, F and O were recorded by 3 different stimuli in 2 groups of subjects. The percentage of occurrence of each of these peaks within the 2 target groups is given in Table 4.2. As it can be seen in the table, waves V, A, D, E, and F were present 100% of the time while waves C and O were present in very few individuals in all the conditions. Hence for all further statistical procedures only measures of V, A, D, E and F were considered.

Table 4.2*: Prevalence (in percentage) of each of the waves in the 2 groups, with the 3 stimuli*

Group→	Normal			SNHL		
Stimulus → Wave↓	Unprocessed /da/	Analog hearing aid processed /da/	digital hearing aid processed /da/	Unprocessed /da/	Analog hearing aid processed /da/	digital hearing aid processed /da/
V	100%	100%	100%	100%	100%	100%
A	100%	100%	100%	100%	100%	100%
C	17%	13%	13%	13%	13%	13%
D	100%	100%	100%	100%	100%	100%
E	100%	100%	100%	100%	100%	100%
F	100%	100%	100%	100%	100%	100%
O	31%	31%	31%	9%	9%	9%

The following statistical tests were used to examine the effects of hearing aid processing and sensorineural hearing loss on speech evoked onset (V & A) and FFR (D, E & F) responses.

1. Mixed ANOVA was done to see the significant effect of stimulus and group across three stimuli and two groups.
2. MANOVA was done to see group differences in each stimulus
3. Repeated measure ANOVA was done within the group (normal and SNHL separately).
4. Bonferroni test was done to see pair wise differences, in instances where there was significant main effect.

4.3.2 Results of Onset Responses

Brainstem responses were recorded for 3 stimuli and in 2 groups. The mean and standard deviation (SD) of the latency and amplitude of onset responses (V & A) elicited by the 3 stimuli and in 2 groups are given in Table 4.3. The statistical results of the latency and amplitude are discussed separately.

Table 4.3*: Mean and Standard Deviation (SD) of latency and amplitude of wave V and A, recorded for the three test stimuli and in the target groups*

Peak	Group	Parameter	Unprocessed stimulus /da/		Analog Hearing aid processed stimulus /da/		Digital Hearing aid processed stimulus/da/	
			Mean	SD	Mean	SD	Mean	SD
Wave 'V'	Normal	Latency	5.73	0.37	6.26	0.31	6.33	0.36
		Amplitude	0.25	0.09	0.22	0.09	0.20	0.07
	SNHL	Latency	5.75	0.35	6.32	0.31	6.55	0.55
		Amplitude	0.20	0.08	0.16	0.07	0.16	0.08
Wave 'A'	Normal	Latency	6.60	1.17	7.19	0.35	7.30	0.31
		Amplitude	0.35	0.09	0.29	0.05	0.26	0.06
	SNHL	Latency	6.88	0.46	7.37	0.44	7.61	0.61
		Amplitude	0.32	0.10	0.30	0.14	0.25	0.08

4.3.2.1 Results of Latency of Onset Responses

The data in Table 4.3 shows that there were mean differences across the responses elicited by 3 stimuli and in 2 groups. Both V and A were prolonged when elicited by the processed stimuli compared to the original, unprocessed /da/. Further, onset responses elicited by /da/-digital was more prolonged than /da/-analog. These mean differences were present in both the groups.

The data also showed mean differences between the two groups. Mean latencies were prolonged in the Sensorineural hearing loss (SNHL) group compared to normal hearing group. This was true for all the 3 stimuli and both the waves.

To verify whether these mean differences were statistically significant, the data was tested on Mixed ANOVA taking stimulus and the group as independent variables. The results of Mixed ANOVA for wave V latency showed an overall significant effect of stimulus [$F(2, 98) = 116.27$, $p<0.05$] but not group [$F(1, 49) = 1.23$, $p> 0.05$]. On the other hand, the results of Mixed ANOVA for wave A showed over all significant effect of stimulus [$F(2, 98) = 20.47$, $p<0.05$] as well as group [$F(1, 49) = 4.47$, $p<0.05$]. There was no interaction between group and stimulus in either wave V latency [$F(2, 98) =1.43$, $p>0.05$] or wave A latency [$F(2, 98) =2.43$, $p>0.05$].

Because Mixed ANOVA showed overall effect of stimulus, Bonferroni test was used for pair-wise comparison. Results showed that there was significant difference across all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/). Figure 4.2 (a & b) shows the delayed onset response elicited by processed stimuli in representative normal (a) and SNHL (b) subjects.

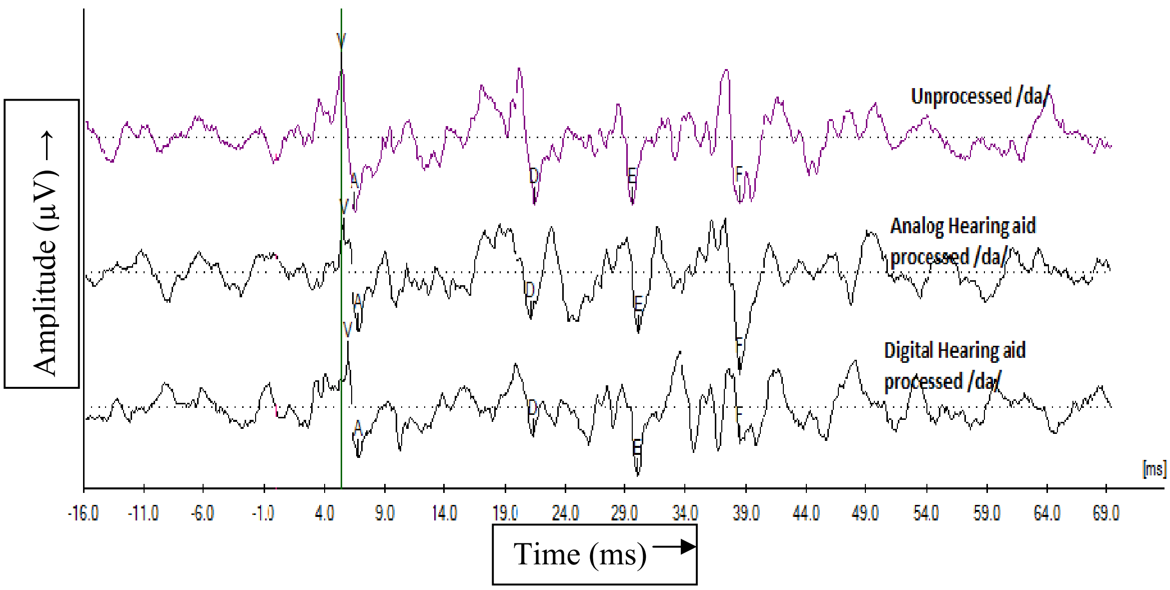

Figure 4.2(a). Responses recorded in a representative Normal hearing subject.

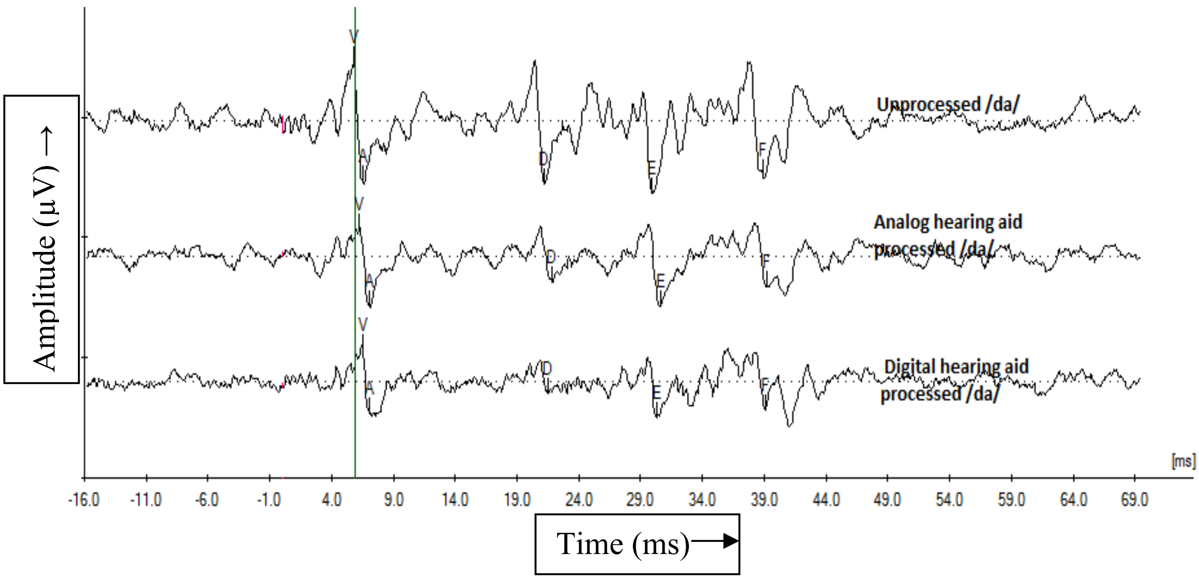

Figure 4.2(b). Responses recorded in a representative SNHL subject.

Furthermore, MANOVA was done to see the group differences in each stimulus. Results showed no difference between normal group and SNHL group in any of the stimuli; Unprocessed /da/ stimulus - [F (1, 49) = 0.073, p>0.05], Analog hearing aid processed /da/ stimulus- [F (1, 49) = 0.529, p>0.05], Digital hearing aid processed stimulus- [F (1, 49) = 3.06, p>0.05].

As the Mixed ANOVA showed significant difference in wave V and A latencies across the stimulus taking data from both the groups, repeated measure ANOVA was done within group to see which group had significant difference in wave V and A latency across the three stimuli. Repeated measures ANOVA was done separately for normal and SNHL groups. Results showed significant difference across stimuli in both normal [F (2, 56) =83.83, p<0.05], [F (2, 56) =7.65, p<0.05] and SNHL [F (2,42) =43.00, p<0.05], [F (2, 42) =39.98, p<0.05] groups for wave V latency and wave A latency respectively.

Pair-wise comparison on Bonferroni test showed significant difference in all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/) in both wave V and A latencies, in both the groups.

4.3.2.2 Results of Amplitude of Onset Responses

The data in Table 4.3 also shows that there were mean differences in the amplitude of responses elicited by 3 stimuli and in 2 groups. Both V and A amplitude were decreased when elicited by the processed stimuli compared to the original, unprocessed /da/. Within processed stimuli, in most instances, Digit-/da/ elicited lesser amplitude compared to analog-/da/. This was true in both the groups.

On comparing the means of 2 groups, in most instances, normal group had higher mean amplitude of wave V and A compared to SNHL group. This was true with all the 3 stimuli.

To verify whether these mean differences were significantly different, mixed ANOVA was done. Results showed significant main effect of stimulus on both wave V [$F (2, 98) = 8.54$, $p<0.05$] and wave A [$F (2, 98) = 14.76$, $p<0.05$] amplitudes. On the other hand, main effect of group was seen only on wave V amplitude [$F (1, 49) = 9.65$, $p< 0.05$] and not on wave A amplitude [$F (1, 49) = 0.35$, $p> 0.05$]. There were no significant interactions either in wave V [$F (2, 98) =2.37$, $p>0.05$] or wave A [$F (2, 98) =0.55$, $p>0.05$].

Consequent to main effect of stimulus seen in Mixed ANOVA, pair-wise comparison was tested on Bonferroni. Results of wave V amplitude showed that there was significant difference between unprocessed stimulus and digital-/da/ only. There were no significant differences in the other 2 pairs. Whereas, results of wave A amplitude showed that all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/) were significantly different.

To verify whether group differences in the amplitude of wave V and A within each stimulus are significantly different, MANOVA was done. Results of wave V showed significant difference between two groups in analog hearing aid processed stimulus [$F (1, 49) = 14.18$, $p<0.05$]. But there was no significant difference between groups in unprocessed stimulus [$F (1, 49) = 3.89$, $p>0.05$] and digital hearing aid processed stimulus [$F (1, 49) = 3.00$, $p>0.05$]. On the contrary, results of wave A did not show significant difference between the two groups in any of the three stimuli (unprocessed stimulus [$F (1, 49) = 0.79$, $p>0.05$], analog hearing aid processed stimulus [$F (1, 49) = 0.03$, $p>0.05$], digital hearing aid processed stimulus [$F (1, 49) = 0.57$, $p>0.05$]).

Repeated measure ANOVA was done within each group (normal & SNHL separately) to test the significance of difference in wave V amplitude across the 3 stimuli. In normals, there was significant main effect of stimulus in both wave V [$F (2, 56) =5.88$, $p<0.05$] and wave A [$F (2, 56) =11.17$, $p<0.05$] amplitudes consequent to which Bonferroni test was done. Results of pair-wise comparison of wave V amplitude showed significant difference between unprocessed stimulus and digital hearing aid processed stimulus and, analog hearing aid processed stimulus and digital hearing aid processed stimulus. But wave V amplitude of unprocessed stimulus and analog hearing aid processed stimulus were not different. On the other hand, pair-wise comparison of wave A amplitude showed significant difference between unprocessed stimulus and digital hearing aid processed stimulus, and also between unprocessed stimulus and analog hearing aid processed stimulus. But wave A amplitude of analog hearing aid processed stimulus and digital hearing aid processed stimulus were not different.

In SNHL group, there was significant main effect of stimulus on wave V [F (2,42 = 6.04, p<0.05) and wave A [F (2,42) =5.19, p<0.05] amplitudes. On pair-wise comparison it was seen that, for wave V, there was significant difference between unprocessed stimulus and both the processed stimuli. But there was no difference between analog /da/ and digital /da/. On the other hand wave A amplitude was significantly different only between unprocessed stimulus and digital /da/ stimulus. Readers can refer to Figure 4.1(a) and (b) for amplitude differences.

4.3.3 Results of FFR Responses

FFRs (D, E & F) recorded were subjectively analyzed to note down the peak latencies and amplitudes and, objectively analyzed on FFT. The mean and standard deviation (SD) of the latency and amplitude of speech evoked FFR responses (wave 'D', 'E', & 'F') elicited by the 3 stimuli and in 2 groups is given in Table 4.4. In the following sections, statistical results are separately discussed for the latency and amplitude of FFR.

4.3.3.1 Results of Latency of FFR Responses

The data in Table 4.4 showed that there were mean differences across the responses elicited by 3 stimuli and in 2 groups. As seen in Table 4.4, all the waves of FFR, in all three stimuli mostly were delayed in SNHL group compared to normal group. Also latency of all the waves (D, E & F) were delayed in hearing aid processed stimuli for both normal and SNHL group. Among the 2 processed stimuli, FFR of digital /da/ were delayed compared to analog /da/.

Table 4.4: *Mean and Standard Deviation (SD) of speech evoked FFR response wave D latency and amplitude recorded by three stimuli, in individuals with normal hearing and sensorineural hearing loss*

Wave	Group	Measure	Unprocessed stimulus /da/		Analog Hearing aid processed stimulus /da/		Digital Hearing aid processed stimulus/da/	
			Mean	SD	Mean	SD	Mean	SD
D	Normal	Latency	21.10	4.21	20.26	5.72	20.57	5.96
		Amplitude	0.26	0.12	0.18	0.08	0.19	0.10
	SNHL	Latency	21.77	0.71	22.49	1.086	22.59	1.38
		Amplitude	0.30	0.13	0.20	0.10	0.19	0.09
E	Normal	Latency	30.02	0.44	30.37	0.37	30.38	0.25
		Amplitude	0.38	0.13	0.31	0.14	0.30	0.09
	SNHL	Latency	30.34	0.77	30.95	0.80	30.97	0.96
		Amplitude	0.40	0.16	0.28	0.10	0.28	0.13
F	Normal	Latency	38.69	0.51	38.96	0.32	38.98	0.26
		Amplitude	0.39	0.13	0.29	0.08	0.35	0.09
	SNHL	Latency	39.15	0.98	38.01	8.55	39.61	0.99
		Amplitude	0.39	0.17	0.27	0.13	0.28	0.11

To verify whether these mean differences were statistically significant, the data was tested on Mixed ANOVA taking stimulus and the group as independent variables. The results of Mixed ANOVA for wave D and F latencies showed no significant main effect of stimulus (for D wave- [$F (2, 98) = 0.09$, $p>0.05$], & for F wave-[$F (2, 98) = 0.80$, $p>0.05$]) as well as group (for wave D - [$F (1, 49) = 3.55$, $p> 0.05$] & for wave F - [$F (1, 49) = 0.06$, $p > 0.05$]. But wave E latency showed significant main effect of both stimulus [$F (2, 98) = 32.81$, $p<0.05$] and group [$F (1, 49) = 9.04$, $p< 0.05$]. So, further analysis was done only for wave E.

As Mixed ANOVA showed overall significant difference in mean latency of wave E, Bonferroni test was done for pair-wise comparison among the three stimuli. In the results it was seen that wave E latency of unprocessed stimulus and analog hearing aid processed stimulus were significantly different. Similarly, wave E latency of unprocessed stimulus and that of digital hearing aid processed stimulus were significantly different. But wave 'E' latency of analog hearing aid processed stimulus and digital hearing aid processed stimulus were not significantly different.

MANOVA was done to see the group differences in each stimulus. There was significant difference between two groups in analog hearing aid processed stimulus [$F_{(1, 49)} = 8.21$, $p<0.05$] as well as digital hearing aid processed stimulus [$F_{(1, 49)} = 10.10$, $p<0.05$]. But there was no significant difference between groups in unprocessed stimulus [$F_{(1, 49)} = 3.38$, $p>0.05$].

Repeated measure ANOVA was done within the group (normal & SNHL separately) to see difference across the 3 stimuli. In normals, there was significant difference across stimuli [$F_{(2, 56)} =27.24$, $p<0.05$]. Bonferroni test showed that wave 'E' latency of unprocessed stimulus and analog hearing aid processed stimulus are significantly different. Similarly, wave E latency of unprocessed stimulus and that of digital hearing aid processed stimulus were significantly different. But wave 'E' latency of analog hearing aid processed stimulus and digital hearing aid processed stimulus were not different

In SNHL group, wave E latency was significantly different across stimuli [$F_{(2, 42)} =12.19$, $p<0.05$]. In the output of Bonferroni test it was seen that unprocessed stimulus and analog hearing aid processed stimulus and, unprocessed and digital hearing aid processed stimuli were significantly different. But analog hearing aid processed stimulus and digital hearing aid processed stimulus were not significantly different

4.3.3.2 Results of Amplitude of FFR Responses

The data in Table 4.4 showed that there were mean differences in amplitude across the 3 stimuli and in 2 groups. As seen in Table 4.4, amplitude of all the waves of FFR, in all three stimuli generally were reduced in SNHL group in compared to normal group. Amplitude of all the waves (D, E & F) were reduced in hearing aid processed stimuli for both normal and SNHL. Within the 2 processed stimuli, FFR amplitude elicited by digital /da/ similar to that of analog /da/.

To verify whether these mean differences were statistically significant, the data was tested on Mixed ANOVA taking stimulus and the group as independent variables. The results of Mixed ANOVA for wave D and F amplitude showed no overall significant difference across stimuli as well as between groups. But wave E amplitude showed significant difference both across stimuli [$F(2, 98) = 15.11$, $p<0.05$] and between groups no significant difference [$F(1, 49) = 0.11$, $p>0.05$]. So, further analysis was done only for wave E.

Bonferroni test was done for wave E amplitude, which showed that unprocessed stimulus was significantly different from both the processed stimuli (analog /da/ & digital /da/). But there was no significant difference of wave E amplitude between analog /da/ and digital /da/.

MANOVA was done to see the group differences in each stimulus. Results showed that there was no significant difference between the two groups in any of the stimuli (unprocessed stimulus [$F(1, 49) = 0.24$, $p>0.05$], analog hearing aid processed stimulus [F (1, 49) = 0.57, p>0.05], and digital hearing aid processed stimulus [F (1, 49) = 0.50, p>0.05]).

Repeated measures ANOVA was done within the group (normal & SNHL separately) to see difference across the stimuli. In normals, there is significant difference across stimuli [F (2, 56) =5.02, p<0.05]. Bonferroni test showed that for wave E amplitude, unprocessed and digital hearing aid processed stimuli are significantly different while there was no significant difference between unprocessed and analog hearing aid processed stimulus as well as, analog hearing aid processed stimulus and digital hearing aid processed stimulus.

In SNHL group, there was significant difference across stimuli [F (2,42) =10.49, p<0.05]. From Boneferoni test, it was seen that wave 'E' amplitude of unprocessed stimulus was significantly different from that of analog hearing aid processed stimulus. Unprocessed stimulus was also significantly different from digital hearing aid processed stimulus. But responses elicited by analog hearing aid processed stimulus and digital hearing aid processed stimuli were not significantly different from each other.

4.3.3.3 Results of FFT

The amplitudes of synchronous neural response at frequencies corresponding to F0, F1, and higher harmonics (HF) were analyzed for the speech evoked ABR for three different stimuli (Unprocessed /da/, analog hearing aid processed /da/, and digital hearing aid processed /da/) and in 2 groups of subjects. The mean and standard deviations (S.D) of amplitude of the F0, F1 and higher harmonics (HF) of speech evoked FFR recorded by the 3 different stimuli, in 2 groups are given in Table 4.5.

Table 4.5*: Mean and standard deviations (S.D) of F0, F1 and higher harmonics (HF) amplitude elicited by three different stimuli cross the group*

Peak	Stimulus→	Unprocessed /da/		Analog hearing aid processed /da/		Digital hearing aid processed /da/	
	Group↓	Mean	S.D	Mean	S.D	Mean	S.D
F0	Normal	7.50	3.41	7.11	2.04	6.61	2.29
	SNHL	7.09	3.77	6.05	2.55	5.15	2.4
F1	Normal	1.03	0.42	0.96	0.33	0.87	0.31
	SNHL	0.92	0.38	0.82	0.40	0.77	0.43
HF	Normal	0.39	0.08	0.37	0.12	0.33	0.09
	SNHL	0.31	0.10	0.28	0.06	0.26	0.06

It can be noticed from Table 4.5 that F0 had highest amplitude compared to F1 and HF in all the three stimuli and in both the groups. Amplitudes of all three frequencies (F0, F1 & F2) were more in normal compared to SNHL group. Also, amplitude was maximum for unprocessed stimuli and minimum for digital hearing aid processed stimulus.

To see the effect of different stimuli on the amplitude of F0, F1 and higher harmonics in both groups, Mixed ANOVA was done. Results of F0 showed that there was neither a stimulus effect [$F(2, 98) = 1.46$, $p>0.05$] nor a group effect [$F(1, 49) = 3.96$, $p>0.05$] on F0 amplitude. Also, there was no interaction between stimulus and group.

For F1 amplitude, the results of Mixed ANOVA showed significant effect of stimulus [$F(2, 98) = 7.84$, $p<0.05$) while there was no significant effect of group [$F(1, 49) = 1.31$, $p>0.05$]. There was also no interaction between stimulus and group [$F(2, 98) = 0.174$, $p>0.05$). Bonferroni test showed significant difference only between unprocessed stimulus and digital hearing aid processed stimulus. There was no significant difference in the other 2 pairs of stimuli.

MANOVA was done to see group difference in each stimulus. It did not show significant difference between two groups in any stimulus (Unprocessed [F (1, 49) = 0.78, p>0.05], analog hearing aid processed [F (1, 49) = 1.81, p>0.05], analog hearing aid processed [F (1,49) = 0.84, p>0.05]).

Repeated measure ANOVA was done to see the difference between stimuli within a group (normal and SNHL). In normal, there is significant difference across stimuli [F (2, 56) = 14.95, p<0.05]. From Bonferroni test, it was seen that there was significant difference between unprocessed stimuli and digital hearing aid processed stimulus. But there was no significant difference in other 2 pairs of stimuli. In SNHL, there was no significant difference in any of the pairs of the stimuli

In the amplitude of HF, Mixed ANOVA showed significant effect of stimulus [F (2, 98) = 8.20, p<0.05] as well as group [F (1, 49) = 10.89, p<0.05]. No interaction was seen between stimulus and group [F (2, 98) = 0.34, p<0.05). Bonferroni test revealed significant difference between unprocessed stimulus and digital hearing aid processed stimulus. But no significant difference was seen in other 2 pairs of stimuli.

MANOVA was done to see group difference in different stimuli. It showed significant difference between two groups in all three stimuli (Unprocessed [F (1, 49) = 7.33, p<0.05], analog hearing aid processed [F (1, 49) = 7.80, p<0.05], analog hearing aid processed [F (1, 49) = 6.48, p<0.05]).

Repeated measure ANOVA was done to see the difference between stimuli within a group (normal and SNHL). There was significant difference across stimuli in both normal [$F(2, 56) = 5.11$, $p<0.05$] and SNHL [$F(2, 42) = 3.88$, $p<0.05$] groups. From Bonferroni test, it was seen in both the groups that there was significant difference only between unprocessed stimuli and digital hearing aid processed stimulus. There was no significant difference in other 2 pairs.

Summary of the Results

Results of the present study can be summarized as follows:

1. On acoustic analysis, it was found that temporal parameters did not differ much across the 3 stimuli but there were marked differences in spectral parameters. Formants increased in their frequencies in the processed stimuli compared to the unprocessed original /da/.

2. On perceptual analysis, it was found that the hearing-aid-processed speech was less natural compared to unprocessed speech. Perceptually, there were no differences between the 2 processed stimuli.

3. In the onset component of brainstem responses, it was seen that speech processed through hearing aid had longer latency and lesser amplitude compared to that in unprocessed speech. Responses elicited by digital /da/ was delayed and of lesser amplitude than that of analog /da/. This was true in both the groups and in both the onset waves (V & A).

4. In the FFR component of brainstem responses, waves D and F did not differ significantly across the stimuli and between the groups. Whereas, wave E was prolonged and lower in amplitude when elicited by hearing-aid processed speech. This was true in both the groups. Also, responses of SNHL group were prolonged compared to normal group.

5. Results of FFT showed that neural response amplitude corresponding to F1 and HF frequency range were lesser in the processed stimuli and SNHL group compared to unprocessed stimulus and normal group respectively.

CHAPTER V

DISCUSSION

The present study was designed with a null hypothesis that there is no difference in the speech processed through the hearing aids compared to the input signal. It was also hypothesized that there are no differences between the normal and SNHL groups in terms of their brainstem neural processing. However, the results of the study did not support these hypotheses. Brainstem responses elicited in the 2 groups and by the 3 stimuli were different in terms of latency as well as amplitude.

5.1 Hearing Aid Induced Distortions

The results of present study showed that processing of synthetically generated /da/ through hearing aids added distortions to the speech stimulus. This was true in both analog as well as digital hearing aids. Distortions were in terms of both spectral as well as temporal parameters. In terms of spectral measures, there was a difference in absolute frequency as well as ratio of the formants (F3/F2, F2/F1, and F1/F0) after processing the through the hearing aid. The differences in the ratio are given in Table 5.1.

Table 5.1*: Ratio of formant frequencies for three stimuli.*

Measure	Unprocessed /da/	Analog hearing aid processed /da/	Digital hearing aid processed /da/
F1/F0	4.22	6.79	6.48
F2/F1	2.97	1.96	1.98
F3/F2	1.77	1.62	1.71

This finding has important implications in speech perception. Miller (1953) reported that formant frequency ratio acts as a cue for vowel discrimination. It can be seen from Table 5.1 that there is large difference in the formant ratio between processed and unprocessed /da/ stimuli. Such changes in formant ratio may not influence speech intelligibility significantly as vowel contributes little (only about 5%) to intelligibility (Kent & Read, 1995). However, one should realize that such changes may be detrimental during the development of speech and language in pre-lingually deaf children. It can also be seen from the table that the difference in the ratios were most evident when the F1 was taken into consideration for the calculation of the ratio. This indicates that the major reason for the discrepancy of these ratios is probably the difference in the frequency of F1 between the processed and unprocessed stimuli.

Furthermore, even in terms of temporal measures, distortion was added into the speech stimulus while processing through the hearing aids. Major distortion was due to the reduction in the transition duration while the burst duration changed little after processing through hearing aids. A similar distortion was noticed in both the hearing aid processed stimuli as shown in Table 4.1 (chapter 4). Reduction in duration of transient cues (Transition duration & burst duration), even by few milliseconds is expected to degrade consonant perception (Tallal, Merzenich, Miller & Jerkins, 1998). Also, Voice onset time (VOT) being major cue for the perception of voicing, such temporal distortions if cut down VOT will affect the distinction between voiced and unvoiced speech sounds.

Another type of distortion that can be seen in the waveforms of the processed stimuli in comparison to the unprocessed stimulus is the evidence of prolonged ringing within the total duration of the stimuli. This increased ringing, which can be seen to have a relatively higher frequency, has probably led to the frequency of F1 being shifted up to 789.29 and 758.31 (for the analog and digital processed stimuli respectively) from the F1 frequency of 493.45 in the unprocessed stimulus.

5.2 Perceptual Changes in Hearing Aid Processed Speech

Perceptually, unprocessed stimulus was found to be more natural than both hearing aid processed stimuli while both the processed stimuli had comparable ratings for the naturalness. This means that although hearing aids are facilitating hearing impaired individuals in terms of audibility, the naturalness of the signal is lost during amplification. However, one is cautioned about the fact that the present study analyzed output of a single syllable and any inferences drawn about naturalness of continuous speech will be premature. Perceptual differences in naturalness observed between unprocessed and hearing aid processed stimuli may have been partly due to changes in formant ratio.

5.3 Brainstem Encoding of Hearing Aid Processed Speech

The primary aim of the study was to understand how unprocessed and processed stimuli are coded neurophysiologically in individuals with normal hearing and sensori-neural hearing loss. Results showed that both onset and sustained responses elicited by the hearing aid processed speech were poorer than that elicited by unprocessed speech syllable. The latencies were prolonged and the amplitudes were reduced. This was true is both the groups. This shows that the distortions produced by the hearing aids are affecting the signal to an extent that the onset and sustained portions of the stimulus will not be coded effectively. Reduced amplitude and prolonged latency indicates poorer synchronization at the level inferior colliculous, which is attributed to the altered rise time of the signal. The responses elicited by /da/-digital were poorer than that of /da/-analog. The exact reason for this is not clear.

The results of the present study are not in agreement with Garvita and Sandeep (2011). Unlike the results of present study, Garvita and Sandeep (2011) reported shorter latency and higher amplitude in the processed stimuli than unprocessed stimulus. The difference in the results could be because of difference in the stimuli and hearing aids used. Garvita and Sandeep (2011) used a natural utterance while the present study used a synthetically generated stimulus and thus ensured better control.

Delay and reduction in amplitude was also observed in wave E which is a component of FFR. FFR codes for the periodicity and is generated at Brainstem nuclei (Marsh, Brown, & Smith, 1974; Smith, Marsh, & Brown, 1975). The present result indicates that the hearing aid induced distortions affect the encoding of periodicity in signal which in turn is important to encode pitch of the signal. The additional ringing reported in the acoustic analysis may be contributing for the poor processing of periodicity. Results of FFT further supported this notion. Amplitude at F1 frequency range was significantly less when the response was elicited by /da/-digital compared to that of unprocessed stimulus. These results are contradicting the findings of Garvita and Sandeep (2011) who reported enhanced F0 and F1 when elicited by processed stimuli. The results of FFT of brainstem response showed that energy at F0 was higher compared to F1 and F2 in all condition (in both groups and all the three stimulus conditions) which is in agreement with the study done by Russo, Nicol, Musacchia and Kraus, (2004) where they reported F0 region in the responses showed a greater energy compared to its harmonics.

5.4 Effect of Sensorineural Hearing Loss on Brainstem Encoding of Speech

The secondary aim of the study was to examine the effect of sensorineural hearing loss on the brainstem encoding of unprocessed and hearing aid processed speech.

Results showed that there was group difference only for the brainstem onset responses (wave ‘V’ and ‘A’), and for the FFR response E (but not for waves ‘D’ & ‘F’). Amplitudes of both waves ‘V’ & ‘A’ were found to be significantly reduced in the individuals with hearing impairment compared to the normal hearing group. This could be due to difference in the audibility of the 2 groups. Because of sensorineural hearing loss, intensity reaching the brainstem will be lesser and in turn leading to lesser amplitude. However, this notion is not supported by the results of latency. If only there was difference in the intensity between the groups, there should have been significant increase in the latency too. Significant difference was absent in the present results.

Lesser amplitude of onset response means that the onset of the stimulus is poorly coded in sensorineural hearing loss compared to normals. Coding of the onset of responses require synchronous firing of auditory nerve fibers and is important for processing burst of the stop consonants. The reduced amplitude observed in mild to moderate sensorineural hearing loss individuals could be either because of reduced synchronous firing of nerve fibers or due to reduced number of participating nerve fibers.

Goldstein and Srulovicz (1977) reported that there was a reduced temporal processing ability even in individuals with sensory hearing impairment owing to a changed (reduced/altered) traveling wave velocity. Such a change in traveling wave velocity might alter the synchronous firing of the auditory nerve fibres, thus leading to reduced amplitudes of the compound action potential which in turn leads to reduced amplitudes of the wave V. Furthermore, the present finding may be also influenced by the distortions in the stimuli. Introduction of temporal and spectral distortion that are added to the stimuli may be leading to reduced synchronous firing.

In the wave A, there was a clear difference between the two groups in terms of the wave 'A' latency. Among the groups, the latency of the wave A in the hearing impaired group was significantly delayed compared to that of the normal hearing group. This effect is possibly due to two reasons. As mentioned before, a cochlear hearing loss also reduces the synchronicity of the neural firing, thus leading to relatively delayed wave A. Another possible reason might be the broadening of the waves because of a relatively more dominant low frequency response from the post synaptic potentials. It is generally agreed that the response spectrum of the post synaptic potential is dominated in the low frequency (Selverston, Kleindienst & Huber., 1985; Pollack, 1988; Schildberger, Milde & Horner, 1988). In cases where there is a loss of synchronized firing, the dominance of the action potential might be lost and hence the dominance of the post synaptic potential sets in. this relative change from a more higher frequency action potential related wave to a more low frequency synaptic potential related wave may make the wave A to be visualized as a much broader activity, thus making the latencies more delayed than what they when they are dominated by the higher frequency action potentials.

There was also significant difference of the wave A between the different stimuli. For the normal hearing group, there was significant difference between the processed stimuli and the unprocessed stimulus whereas, for the hearing impaired group, there was significant difference between all the three stimuli. The difference in the latency for the processed versus the unprocessed might be because of the addition of spectral and temporal distortions into the processed signal.

It was observed that the wave A latencies didn't significantly change for the two processed signal in the normal group, whereas there was significant difference between the two processed signal in the hearing impaired group. This might be possible because, a normal auditory system might compensate for the slight changes in the signal (as seen in the analog Vs digital hearing aid processed stimuli), whereas an impaired auditory system might not be able to off-set these changes in the stimuli, which are also evidenced in the wave A latencies for the analog and digital hearing aid processed stimuli. Acoustical analysis also revealed similar finding where in the burst duration was slightly longer for the digital stimuli compare to analog. And the same is seen in the wave A latency as well where in latencies of wave A for the digitally processed signal was slightly delayed than compare to that of analog processed signal.

Latency of wave E also showed group difference with SNHL individuals showing prolonged responses compared to normals. Wave E, the component of FFR codes for the periodicity (Kraus, Mc Gee, Carrell, Zecker, Nicol & Koch, 1996). If there was no difference in waves D and F while wave E was significantly prolonged, it indicates disruption in the coding of periodicity. This is particularly true with SNHL individuals.

FFT shows decrease in energy of F0, F1 and HF in Hearing aid processed stimuli compared to unprocessed stimuli. In all frequencies (F0, F1 and HF) there is trend of decreasing energy. In F0 and F1 there is no group difference but in HF, significant amplitude difference is present between individuals with normal and SNHL. This may be due the reduced ability to code high frequency formants in SNHL group secondary to reduced phase locking (Miller, Schilling, Franck & Young, 1997). Acoustic analysis shows that in hearing aid processed stimuli, there is increase in frequency of F1 and F2 but F0 remained the same. Decrease in amplitude (energy) may reduce the perception of manner as F2 cues for place of articulation (Kent & Read, 1995).

Thus, it can be inferred that speech cues are likely to be disrupted when processed through hearing aids. Such disruptions are more in individuals with sensorineural hearing loss as the cochlear pathology acts as an additional degrading factor. The present day hearing aids mainly help in improving the audibility, and improve signal to noise ratio to some an extent. However, there are hearing aid induced distortions which may be detrimental to speech perception. This issue needs to be seriously considered and the respective group must work towards improving the hearing aid technology.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The primary objective of this study was to find the differences in neural coding of unprocessed speech and hearing aid processed speech at brainstem level in individuals with normal hearing and sensorineural hearing loss. The secondary objective was to compare the spectral and temporal characteristics of the original unprocessed speech with the analog and digital hearing-aid-processed speech.

A total of 51 subjects participated in the study. They were divided into 2 groups: One of 29 normal hearing adults and the other of 22 adults with mild to moderate sensorineural hearing loss. Experiment was carried out in three phases; Generation of the test stimuli, perceptual and acoustic analysis of the generated stimuli and, recording of the auditory brainstem responses.

In the phase 1, Synthetic speech syllable /da/ of 40 ms duration (generated using Klatt synthesizer) (Klatt, 1980) was used as stimulus. This stimulus was then processed through analog and digital hearing aids separately to get 2 hearing-aid-processed stimuli (analog hearing aid processed stimulus and digital hearing aid processed stimulus). In the phase 2, all the 3 stimuli were acoustically analyzed in terms of spectral and temporal aspects. Perceptual analysis was also done to rate the stimuli for naturalness. In the phase 3, brainstem responses (wave forms V, A, D, E, & F) were recorded by all the three stimuli separately in both the groups. The data thus obtained was statistically analyzed on mixed ANOVA, MANOVA, repeated measure ANOVA and Bonferroni post-hoc test.

In the results it was seen that, on acoustic analysis, there were marked differences in spectral parameters across 3 stimuli but temporal parameters did not differ. Formants increased in their frequencies in the processed stimuli compared to the unprocessed original /da/. On perceptual analysis, it was found that the hearing-aid-processed speech was less natural compared to unprocessed speech. Perceptually, there were no differences between the 2 processed stimuli.

In the onset component of brainstem responses, it was seen that speech processed through hearing aid had longer latency and lesser amplitude compared to that in unprocessed speech. Responses elicited by digital /da/ was delayed and of lesser amplitude than that of analog /da/. This was true in both the groups and in both the onset waves (V & A). In the FFR component of brainstem responses, waves D and F did not differ significantly across the stimuli and between the groups. Whereas, wave E was prolonged and lower in amplitude when elicited by hearing-aid processed speech. This was true in both the groups. Also, responses of SNHL group were prolonged compared to normal group. Results of FFT showed that neural response amplitude corresponding to F1 and HF frequency range were lesser in the processed stimuli and SNHL group compared to unprocessed stimulus and normal group respectively.

Thus from the results of the present study it can be concluded that hearing aids create distortion in both spectral and temporal aspects of speech which in turn affects the processing at the level of brainstem. Such distortions are more deleterious in individuals with sensorineural hearing loss. Individuals with sensorineural hearing loss needs better quality of signal compared to individuals with normal hearing for equivalent perception. So, hearing aid technology should be improved to minimize the distortions which are detrimental to speech perception.

Implications of the Study

From the findings of the present study it is learnt that

a. Brainstem responses are reliable and hence useful technique to characterize the hearing aid output, understand the brainstem encoding of speech which inturn should part of the hearing aid selection process.

b. Perceptually digital hearing aid is better than analog hearing aid inspite of acoustic characteristics being similar.

Future Directions

Future studies can take up more number of speech sounds and use the same paradigm to see the differences across the stimuli. The phenomenon of 'Acclimatization to hearing aids' can be studied by recording brainstem responses to hearing aid processed speech at different intervals of time. Such studies can also be taken to examine the differences across different degrees and types of hearing loss.

REFERENCES

Abrams, D. A., Nicol, T., Zecker, S., & Kraus, N. (2006). Auditory brainstem timing predicts cerebral asymmetry for speech. *Journal of Neuroscience*, *26,* 11131–11137.

Alcantara, J. L., Moore, B. C., Kuhnel, V., & Launer, S. (2003). Evaluation of the noise reduction system in commercial digital hearing aid. *International Journal of Audiology, 42*, 34-42.

Arlinger, S., Billermark, E., Oberg, M., & Lunner, T. (1998). Clinical trial of a digital hearing aid. *Scandinavian Audiology, 27,* (1), 51-61.

Berninger, E., & Karlsson, K. K. (1999). Clinical study of Widex Senso on first-time hearing aid users. *Scandinavian Audiology. 28,* (2), 117-125.

Bille, M., Jensen, A., Kjaerbol, E., Vesterager, V., Sibelle, P., & Nielson, H. (1999). Clinical Study of a Digital vs. an Analogue Hearing Aid. *Scandinavian Audiology, 28*, 127-135.

Billings, J. C., Tremblay, K. L., Souza, P. E., & Binns, M. A., (2007). Effect of hearing aid amplification and stimulus intensity on cortical evoked potentials. *Journal of Otology and Neurootology, 12,* 234-246.

Boymans, M., Dreschler, W. A., Schoneveld, P., & Verschuure, H. (1999). Clinical evaluation of a full-digital in-the-ear hearing instrument. *Audiology, 38*, (2), 99-108.

Brown, E., Klein, A. J., & Snydee, K. A. (1999). Hearing aid processed tone pips: Electroacoustic and ABR characteristics. *Journal of the American academy of Audiology, 10,* 190-197.

Cody, D. T. R., Klass, D. W., & Bickford, R. G. (1967). Cortical Audiometry: n objective method of evaluating auditory acuity in awake and sleeping man. *Transection American Academy of Ophthalmology and Otolaryngology*, *71,* 81-91.

Cunningham, C. H., Stainsby, J. A., Wright, G. A., Wood, M. L. (2001). Partial discrete Fourier transform (PDFT) multiband encoding magnetic resonance in medicine. *Magnetic resonance in medicine, 45,* 1, 118–127.

Dalebout, S. D., & Robey, R. R. (1997). Comparison of intersubject and intrasubject variability of exogenous and endogenous auditory evoked potentials. *Journal of the American Academy of Audiology, 8*, (5), 342-354.

Dempsey, J. J. (1997). Circuitry options: Signal processing at average conversational levels. In Sowell, T. T. (ed), *Practical hearing aid selection and fitting* (pp 17-34), Baltimore: scientific and technical publication section.

Dillon, H. (2001). Hearing Aids Systems: in Dillon H. (ed): *Hearing Aids* (pp 48-73), New York: Thieme, Boomerang Press.

Dimitrijevic, A., John, M. S. & Picton, T. V. (2001). Human auditory steady responses to tones independently modulated in both frequency and amplitude, *Ear and Hearin.*25, (1), 68-84.

Dorman, M. F., Lindholm, J. M., & Hannley, M. T. (1995). Influence of first formant on deprivation of recognition of voiced stop consonants by hearing impaired listeners. *Journal of speech Language and Hearing Research, 28,* 372-380.

Dreschler, W. A. (1988). Dynamic range reductionby peak clipping or compression and its effect on phoneme perception in hearing impaired listeners. *Scandinavian Audiology, 17,* 35-43.

Dreschler, W. A, Eberhardt, D., & Melk, P. D, (1984). The use single channel compression for the improvement of speech intelligibility. *Scandinavian Audiology, 13*, 231-236.

Dubno, J., Dirks, D., & Morgan, D. (1984). Effects of Age and Mild Hearing Loss on Speech Recognition in Noise. *Journal of the Acoustical Society of America*, *76*, (1), 87-96.

Garvita. M., & Sandeep. M. (2011). Effect of signal processing of hearing aids on speech spectrum and its neurophysiological consequences, *Journal of Indian Speech & Hearing Association, 25,* (1), 49-58.

Geetha, C., Ashley, G., & Yathiraj, A. (2006). Perception of high frequency speech in normal. *Journal of Indian Speech and Hearing Association, 20* (part II), 47-51.

Goldstein, J. L., & Srulovicz,. P. (1977). Auditory nerve spike interval as an adequate basis for neural spectram analysis. In: Evans EF, Wilson JP (eds) *Psychophysics and Physiology of Hearing* (pp.337-345). London: Academic Press.

Halle, M., Hughes, G. W., & Radley, J. P. A. (1957). Acoustic properties of stop consonants. *Journal of Acoustical Society of America, 29, (1),* 107- 116.

Helfer, K. & Wilber, L. (1990). Hearing Loss, Aging, and Speech Perception in Reverberation and Noise. *Journal of Speech and Hearing Research*, *33*, 149-155.

Hickson, L, Dodd, B., & Byrne, D. (1995). Consonant perception with linear and compression amplification. *Scandinavian Audiology, 24,* 175-184.

Horwitz, A., Turner, C. W., & Fabry, D. A. (1991). Effects of different frequency response strategies upon recognition and preference for audible speech stimuli. *Journal of Speech & Hearing Research, 34*, 1185-1196.

Jongman, A., & Blumstein, S. E., 1985. Acoustic Properties of dental and alveolar stop consonants. A cross Language study. *Journal of Phonetics.13*, 235-251.

Kent, R. D. & Read, C. (1995). *The acoustic analysis of speech.* San Diego, London: Singular.

Khaladkar, A. A., Karthik, N., & Vanaja, C. S. (2005). *Speech burst and click evoked ABR.* Paper presented at 37th Annual conference of ISHA, Indore.

Klatt, D. H. (1980). Software for a cascade/parallel formant synthesizer. *Journal of the Acoustical Society of America*, *67*, 971–995.

Korczak. P. A., Kurtzberg. D., & Stapells. D. R. (2005). Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioral measures of speech-sound processing. *Ear and Hearing*, *26,* 165-185.

Kraus, N., Mc Gee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., & Koch, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science*, *273,* 971–973.

Krishnan, A. (2002). Human frequency-following responses: representation of steady state synthetic vowels. *Hearing Research*, *166*, 192–201.

Krishnan, A., Xu, Y., Gandour, J. T., & Cariani, P. A. (2004). Human frequency-following response: representation of pitch contours in Chinese tones. *Hearing Research, 189*, 1–12.

Liberman, A. M., Delattre, P., Cooper, F. S., & Gerstman, L. J. (1954). The role of consonant-vowel transitions in the perception of the stop and nasal consonants. *Psychological Monographs, 68,* (8), 1-13.

Licklider, J. C. R. (1946). Effect of amplitude distortion upon the intelligibility of speech. *Journal of Acoustic Society of America*, *18*(2), 429-434.

Lopez, A. B. (1998). *Comparative study of analog and digital hearing aids*. Unpublished Master thesis, Louisiana State University. *Louisiana* .

Marsh, J. T., Brown, W.S., & Smith, J. C. (1974). Differential brainstem pathways for the conduction of auditory frequency-following responses. *Electroencephalography and Clinical Neurophysiology, 36,* 415-242.

Mc Gee, T., & Kraus, N. (1996). Auditory development reflected by middle latency response. *Ear and Hearing, 17,* (5), *419-429.*

Miller, S. (1953). Vowel classification based on fundamental frequency and formant frequency. *Journal of Speech and Hearing Research, 36,* 694-700.

Miller, R. L., Schilling, J. R., Franck, K. R., & Young, E. D. (1997). Effects of acoustic trauma on the representation of the vowel in cat auditory nerve fibers. *Journal of Acoustical Society of America, 101*, 3602–3616.

Nagarajan, S. S., Cheung, S. W., Bedenbaugh, P., Beitel, R. E., Schreiner, C. E., & Merzenich, M. M. (2002). Representation of spectral and temporal envelope of twitter vocalizations in common marmoset primary auditory cortex. *Journal of Neurophysiology, 87*, 1723–1737.

Nielsen, H. B., Nielsen, H., & Parving, A. (1990). Harmonic distortion measurements in clinical hearing and fitting. Preliminary report. *Scandinavian Audiology, 19,* (1), 55-58.

Nusbaum, H. C., & Morin, T. M., (1992). Paying attention to differences among talkers. In: Tohkura Y, Sagisaka Y, Vatikiotis-Bateson E, eds. *Speech Perception, Production, and Linguistic Structure* (pp 113–134). Tokyo: Ohmasha Publishing.

Ostroff, J. M., Martin, B. A. & Boothroyd, A. (1998). Cortical evoked responses and Acoustic change within a syllable. *Ear and Hearing, 19*, 290-297.

Peterson, G. E. & Lehiste. I. (1960). Duration of syllable nuclui in English. *Journal of Acoustical society of America, 32*, 693-703.

Picton, T. W., Duieux-Smith, A., Champagne, S., Whittinghum, J., Moran, L., & Giguere, C. (1998). Objective evaluation of aided threshold using auditory steady state response. *Journal of American Academy of Audiology, 9, 315-331.*

Rauschecker, J. P. (1997). Processing of complex sounds in the auditory cortex of cat, monkey, and man. *Acta Otolaryngologica Suppl. 532*, 34–38.

Rawool, V. W. (2006). The effects of hearing loss on temporal processing. *Hearing Review, 13,* 30-34.

Reckards, F. W., & Devidi, S. (1995). Exaggerated hearing loss in noise induced hearing loss compensation claims in Victoria. *Medical journal of Australia, 163*, 360-363.

Repp. B. H. (1984). Closure duration and release burst amplitude cues to stop consonant manner and place of articulation. *Language and Speech*, *27,* (3), 245-254.

Revoile, S., Pickett, J. M., Holden-Pitt, L. D., & Talkin, D. (1987). Burst and transition cues to voicing perception for spoken initial stops by impaired- and normal-hearing listeners. *Journal of Speech & Hearing Research, 30,* (1), 3–12.

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

Sachs, M. B., & Young, E. D. (1979). Encoding of steady-state vowels in the auditory nerve: representation in terms of discharge rate. *Journal of Acoustical Society of America*, *66*, 470–479.

Sachs, M. B., Voigt, H. F., & Young, E. D. (1983). Auditory nerve representation of vowels in background noise. *Journal of Neurophysiology*, *50,* 27–45.

Sammeth, C. A., Tetzeli, M., & Ochs, M. T. (1996). Consonant recognition performance of hearing-impaired listeners using one linear and three nonlinear hearing aids. Aug. *7,* (4), 240-50

Sandlin, R. E. (2000). *Textbook of Hearing Aid Amplification*, San Diego: Singular publishing group, Inc.

Schildberger, K., Milde, J. J., & Hörner, M. (1988). The function of auditory neurons in cricket phonotaxis. II. Modulation of auditory responses during locomotion. *Journal of Comparitive Physiology, 163*, 621-631.

Schweitzer, S. C. (1998). Its about number: A primer on the digitization of hearing aid. *Hearing Journal, 51,* (11), 15-16, 24-27.

Selverston, A. I., Kleindienst, H. U. & Huber, F. (1985). Synaptic connectivity between cricket auditory interneurons as studied by selective photoinactivation. *Journal of Neuroscience, 5*, 1283–1292.

Smith, J. C., Marsh, J. T., & Brown, W. S. (1975). Far-field recorded frequency-following responses: evidence for the locus of brainstem sources. *Electroencephalogr Clinical Neurophysiology*, *39*, 465–476.

Song, J. H., Banai, K., Russo, N. M., & Kraus, N. (2006). On the relationship between speech and non-speech evoked auditory brainstem responses. *Audiology & Neurotology, 11*, 233–241.

Stelmachowicz, P. G., Kopun, J., Mace, A., Lewis, D. E., & Nittrouer, S. (1995). The perception of amplified speech by listeners with hearing loss: Acoustic correlates. *Journal of the Acoustical Society of America, 98*, 1388–1399.

Sullivan, J. A., Levitt, H ., Hwang, J .Y., & Hennessey, A. (1988). An experimental comparison of four hearing aid prescription methods. *Ear & Hearing, 9,* 22-32.

Suter, A. (1985). Speech Recognition in Noise by Individuals with Mild Hearing Impairments. *Journal of the Acoustical Society of America*, *78,* (3), 887-900.

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

Tramblay, K. L., Friesen, L., Martin, B. A., & Wright, R. (2003). Test-retest reliability of cortical evoked potentials using unnatural produced speech sound. *Ear and Hearing, 24,* (3), 225-232.

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

Tramblay, K. L., Billings, C. J., Friesen, L. M. & Souza, P. E. (2006). Neural representation of amplified speech sound. *Ear and Hearing, 27,* 93-103.

Tsu, B., Wong, L. L., & Wong, E. C. (2002). Accuracy of cortical evoked response audiometry in the identification of non-organic hearing loss. *International Journal of Audiology, 41*(6), 330-333.

Turner, C. V., Smith, S., Aldridge, P. L., & Stewart, S. L. (1996). Formant transition duration and hearing impairment. *Journal of Acoustical Society of America, 100* (4), 2631-2632.

Turner, C., & Robb, M.P. (1987). Audibility and recognition of stop consonants in normal and hearing-impaired subjects. *Journal of Acoustical Society of America, 81,* 1566-1573.

Turner, C., Fabry, D., Barrett, S., & Horwitz, A. (1992). Detection and Recognition of stop consonants by normal-hearing and hearing-impaired listeners. *Journal of Speech & Hearing Research, 35*, 942-949.

Turner, C. W., Chi., Ling, S., & Flock, S. (1999). Limiting spectral resolution in speech for listeners with sensorineural hearing loss. *Journal of Speech, Language and Hearing Research, 42,* 773-784.

Valente, M., Bentler, R., Seewald, R., Trine, T., & Van Vliet, D. (1998). Guidelines for hearing aid fitting for adults. *American Journal of Audiology, 7*, 5-13.

Vanaja. C. S. & Manjaula, P. (2004). *An objective tool for hearing aid selection.* Paper presented at 36th Annual conference of ISHA, Mysore.

Wood, S. A., & Lutman, M. E. (2004). Relative benefits of linear analogue and advanced digital hearing aids. *International Journal of Audiology, 43* (3), 144-155.

Zeng, W., & Turner, R. M., (1990). Recognition of voiceless fricatives by normal and hearing impaired subjects. *Journal of Speech and Hearing Research, 33* (1), 440-449.