Title

PERIODICITY CODING AND SPEECH PERCEPTION IN NOISE IN INDIVIDUALS WITH SYMMETRICAL AND ASYMMETRICAL COCHLEAR HEARING LOSS – IMPLICATIONS FOR AMPLIFICATION

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Chapter 1

Introduction and review of literature:

Cochlear hearing loss is the most common types of hearing loss (Plack, 2005). It is most often seen as damage to the outer hair cells (OHCs) and/or inner hair cells (IHC) on the basilar membrane (BM), distortion/destruction of the stereocilia on top of each of the hair cells or the death of the entire hair cell. OHCs are generally known to be more vulnerable for damage (Borg, Calnon & Engstorm 1995). Damage to the OHCs result in loss of efficiency (or complete absence) of the active mechanisms and non-linear processes associated with a healthy and functional OHC. Such a type of damage leads to reduced sensitivity for soft sounds broadened tuning curves on the basilar membrane, and loss of frequency selective nonlinearities. Also, there is evidence for greater spreads of masking in the upward direction of frequencies i.e. low frequencies have a much greater masking effect on high frequencies in comparison to normal hearing individuals (Trees & Turner, 1986).

1.1 Cocktail party effect:

One of the major perceptual consequences for an individual with cochlear hearing loss is the difficulty following one voice in a mixture of many voices in a conversation. This problem is generally referred to as the “cocktail party effect” (Cherry, 1953). Research on this phenomenon has shown that this problem can be reduced if the target voice has some qualities which distinguish it from others. These include the vocal quality, location of the source of the voice in space, rate of speaking and the vocal pitch (Brokx & Nooteboom, 1982) etc. In normal conversation, the vocal pitch always changes with time. These changes are very important in segregation of voices. The segregation of vocal parameters of the target speaker from a large number of speakers is the basis for perception of speech in noise. This type of segregation, based on the similarities between the target and the so called background voices, is called “stream segregation” (Bregman, 1990).

The perception of vocal pitch is closely associated with the perception of the fundamental frequency of the speech signal. In other words, pitch is considered to be the perceptual correlate of fundamental frequency. Hence, it can be deemed that better the perception of speaker’s F0, better are the chances of segregating the target speaker’s F0 in a mixture of different speakers and/or noise. Culling and Darwin (1993) studied the segregation of the target speaker’s fundamental frequency in a two talker set up, and proposed possible ways as to how the listener can “hear out” speech of a target speaker’s F0 in the presence of a competing F0. They presume that when the F0s of the two voices are different, the lower harmonics of each of the voices are resolved and hence excite different places on the basilar membrane. The brain further associates each of the fundamentals with their separate sets of harmonics to form a harmonic series and attributes them to the target and competing signals and thus the listener is able to select out the target speaker’s voice from the second speaker’s voice. This assumption can be further extended to focusing the listener’s auditory attention to the vocal parameters of the target speaker in the presence of many speakers (speech babble) or in any other types of masking noises. Therefore, it can be concluded that efficient resolution of fundamental frequency (and also the harmonics) is essential for segregating the target speech signal from a background noise(s).

1.2 Frequency selectivity/discrimination and cochlear hearing loss:

It is generally accepted that the perception of fundamental frequency is affected in individuals with cochlear hearing loss. This is consequent to the broadening of auditory filters leading to broader than normal excitation on the basilar membrane. This problem is further aggravated with the softer sounds being inaudible. Hence, according to the “place theory”

(Helmholtz, 1885), there is reduced frequency discrimination in individuals with cochlear hearing loss as the excitation caused by two tones are not resolved on the basilar membrane and overlap within the same filter. Many researchers have studied the difference limens for frequency and reported that damage to the cochlea leads to affected frequency discrimination (Gengel, 1973; Moore & Peters, 1992; Simon & Yund, 1993). There is also considerable amount of research regarding variability in the size of DLFs across individuals and also within the same individual across the two ears (Simon & Yund, 1993).

In order to correlate or extrapolate results of psychophysical studies to actual speech perception, there exists a considerable amount of research on the perception of complex tones. The basic assumption is that complex tones are similar to speech in that they both have a predominant fundamental frequency with their specific set of harmonic series. Additionally, not only does the individual need to resolve the fundamental frequency but also the higher harmonics associated with the fundamental. Hence, good frequency resolution can be considered the basis for good performance in perception of both complex tones and speech. Cochlear loss is associated with poor frequency resolution, especially the higher harmonics leading to less clear pitch perception and poorer discrimination of pitches than normal. Most studies regarding the pitch discrimination of complex tones show that difference limens for F0 (F0DLs) are poorer in subjects with cochlear hearing loss compared to normal hearing individuals (Hoekstra & Ritsma, 1977; Arehart, 1994; Moore, Glasberg & Hopkins, 2006). However, the degree to which the perception was affected depended on the fundamental frequency of the stimulus. When the F0 was low, F0DLs were considerably better than compared to high F0 (Moore, Glasberg & Hopkins, 2006).

1.3 Phase locking (neural synchrony) and cochlear hearing loss:

Goldstein and Srulovicz (1977) reported that, in addition to broadened auditory filters, another hypothesized reason why individuals with cochlear hearing loss have poorer pitch discrimination could be the reduction in the ability to make use of phase locked (neural synchrony) information. The effect of cochlear damage on phase locking is not clear. Harrison and Evans (1979) reported that kanamycin, which mainly damaged OHCs, did not significantly affect the phase locking abilities in guinea pigs, whereas Woolf, Ryan, and Bone (1981) revealed that phase locking was adversely affected by damage to the OHCs of chinchillas. They also reported that the phase locking was significantly reduced when the behavioral thresholds were elevated by 40 dB or more. Furthermore, they observed that there was a reduction in the highest frequency at which phase locking could be achieved.

The reason for the poorer phase locking associated with cochlear hearing loss is still unclear. There have been several presumptions regarding the possible causes for the loss of phase locking. Goldstein and Srulovicz (1977) supposed that the lack of phase locking is linked to changes in traveling wave velocity associated with cochlear hearing loss. Woolf et al. (1981) suggested that it might be related to the poorer mechanical coupling between the tallest stereocilia and the tectorial membrane. However, irrespective of the reasons, the reduced synchrony has important considerations (consequences) in the perception of sounds.

This problem is further elevated by complex sounds like speech. This is because of the presence of formants along with the fundamental frequency, which correspond to the resonances of the vocal tracts. The neural system not only has to encode the fundamental, but also should phase lock for these higher frequency formants to ensure efficient perception of speech. Miller, Schilling, Frank and Young (1997) measured the phase locking abilities in cats after cochlear damage due to exposure to loud sounds. They showed that the phase locking in the neurons responsible for the encoding of F2 information was significantly reduced. This reduced phase locking information associated with cochlear hearing loss might contribute to the problems in understanding speech.

1.4 Cochlear hearing loss and speech perception abilities:

Based on the above mentioned factors, it is easy to see why difficulty in understanding speech is the most common problem faced by individuals with cochlear hearing loss (CHL). Although the degree to which CHL affects speech perception is dependent of the severity of the hearing loss, there are other factors that also need to be considered to study the effects of cochlear hearing loss on speech perception. These factors include intensity of the presented speech stimulus, presence of background noise, effects of different types of background noises, reverberation, etc. Even in the absence of these factors, increasing the audibility alone is not sufficient to ensure efficient speech perception. Individuals with CHL have significant problems in understanding speech even at supra threshold levels. However, one of the major difficulties such individuals face is the difficulty in understanding speech in the presence of background noise. In such cases, the factors that determine the difficulty of speech understanding become multiple and hence they have the greatest problems in listening to a particular speech signal in the presence of background noise.

Numerous studies have demonstrated the effects cochlear hearing loss on speech perception. Bonding (1979), measured the speech recognition scores in individuals with different types of hearing losses, in an attempt to correlate the width of critical band to speech recognition scores. He reported that speech recognition scores were significantly reduced in individuals with cochlear hearing loss when compared to a normative set of data obtained for the same stimuli. Gordon-Salant and Fitzgibbons (1993) compared the speech recognition abilities in individuals with sensori-neural hearing impairment. They measured the speech perception in quiet and in noise for four groups of subjects – young normal, young hearing impaired, elderly normal, elderly hearing impaired. They found that both the hearing impaired group performed significantly poorer than the normal hearing groups. Also, within the hearing impaired group, the young hearing impaired subjects performed slightly better than the elderly impaired group. The results were furthermore significant when the groups were compared for their performances in the presence of noise – the presence of background noise significantly deteriorated the performance of the impaired groups in comparison to the normal group, with the elderly hearing impaired group performing the worst.

On the lines of the above study, Dubno, Dirks and Morgan (1984) also evaluated and compared the speech recognition abilities in young and old individuals with normal and mild (cochlear) impaired hearing. To compare across the groups, they measured the minimum level of speech (in dB SPL) to attain 50% scores. They showed that both the groups with hearing impairment required significantly greater levels of speech to attain the 50% criterion, thus indicating poorer speech recognition abilities for the impaired groups in comparison to the normal groups. Again, this effect was further significant when the groups were tested in the presence of noise – both groups with hearing impairment were significantly poorer than the normal groups, with the elderly hearing impaired group performing the worst. Hence, this study indicates that even a mild degree of hearing loss affects the speech perception abilities, especially in the presence of background noise.

However, contrary results were obtained by Townsend and Bess (1980) who measured the word recognition scores in young and old individuals with normal and mild hearing impairment. They found no significant difference for word recognition scores in quiet for both sets of subjects and only a 5% difference for recognition in noise. This indicates that there is great degree of variations in the cochlear hearing impaired population.

1.5 The electrophysiological approach:

As mentioned before, individuals with cochlear hearing impairment also lack the ability to efficiently phase lock to the incident sound. Most previous studies have used invasive methods to observe the neural phase locking abilities. However, these studies are carried out on animals and cannot be replicated on humans with ease. The use of scalp recorded evoked potentials have started to gain momentum in this regard to help understand the neural activity related to speech processing in the auditory pathway, from the level of the auditory nerve to the cortex. Many types of evoked potentials have been used to assess the neural activity associated with encoding of speech signals in the auditory system. These include speech evoked auditory brainstem responses (ABRs), auditory late latency responses (ALLRs) P1-N1-P2 complex, acoustic change complexes (ACCs), mismatch negativity (MMN), etc. These potentials have used repetitive presentations of short duration speech stimuli monosyllables, monosyllabic and bi-syllabic words to evoke phase locked responses.

Speech evoked ALLR – P1-N1-P2 complex is an event related potential which is typically elicited using a short duration stimulus and involves a series of positive and negative peaks in the latencies of 50 to 300 ms. It involves a positive peak at latency of approximately 50 ms named P1, followed by a negative peak at approximately 100 ms named N1 and another positive peak near 200 ms called P2. The N1 component is often associated with the “onset” of the stimulus. This response is considered as an obligatory or “sensory” response (Steinschneider & Dunn, 2002) and does not require the subject to actively attend to the stimuli. This ERP is generally used to assess the auditory activity associated with speech processing at the cortical structures. It is typically associated with the detection of the sound.

However, it does not lend any support in understanding the more complex behavioural processes like identification and detection.

The acoustic change complex (ACC) (Martin & Boothroyd, 1999) can be considered as an extension of this P1-N1-P2 complex. This complex can be elicited by longer stimuli in response to a change in the acoustical aspect of the ongoing signal. The changes can include changes in frequency and/or intensity, duration, etc. When this complex is evoked in response to stimuli like speech, where there are multiple time varying acoustic changes, the resulting waveform contains multiple, often overlapping P1-N1-P2 responses that occur in response to the stimulus onset, changes within the stimulus, and the stimulus offset. For example, ACC can be elicited for the change in acoustic properties within the speech stimulus when there is a transition from the consonantal burst portion to the more steady state portion of the vowel (Kaukoranta, et al., 1987; Ostroff, et al., 1998). Several evidences suggest that the ACC can be used to associate with the brain’s capacity to discriminate acoustic features present within the speech signal. It is also been shown to be reasonably consistent with the behavioural thresholds for psychophysical discrimination (Martin & Boothroyd, 2000). Hence ACC can be considered as a neurophysiologic index of speech discrimination abilities.

One of the more recent and widely used potential to electro physiologically assess speech perception abilities is the speech evoked auditory brainstem response. Extensive research conducted in the Auditory Neuroscience laboratory of the North-Western University by Kraus and associates have suggested that the auditory brainstem responds faithfully to the acoustic parameters of speech. They have used the consonant-vowel combination /da/ to assess the brainstem’s ability to phase lock to the onset, steady-state and offset portions of the stimulus. It has also been used to assess the neural synchrony associated with the encoding of fundamental frequency and the associated higher formants.

A plethora of research has suggested how the auditory brainstem responds to the different acoustic parameters of speech. Often, speech-ABRs are used to evaluate the brainstem's ability to encode the transient (consonant) portion and the sustained-steady state portion (vowel) of a syllable. A typical speech evoked ABR to the speech syllable /da/ is as shown in the figure below:

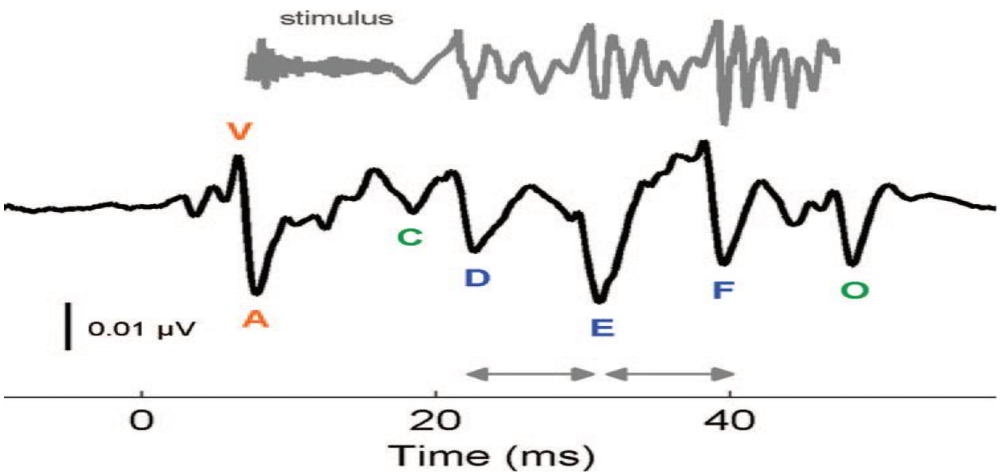

Figure 1.1: Acoustic waveform of the stimulus /da/ used to elicit speech evoked ABRs and the corresponding response, including the different wave components.

The speech ABR consists of 2 major portions – an initial peak-trough complex, typically seen in the latencies less than 10-12 ms when evoked by a CV syllable, represents the transient portion of the stimulus associated with the burst portion of the consonant part of the syllable, followed by a series of peaks which represent the sustained portion of the vowel part of the syllable (Chandrasekaran & Kraus, 2009). The sustained portion is called as the frequency following response (FFR). The initial peak-trough complex, labelled as V-A, is thought to be analogous to the wave V of the click evoked ABR. The FFR portion, which follows the V-A complex, contains a series of peaks labelled C, D, E, F and O. The peak labelled 'O' is thought to represent the offset of the stimulus. The defining feature of the sustained portion is the periodicity, which "follows" the frequency information contained in the response and hence the name, frequency following response. The duration of the response from the initial wave V through peak O is observed to be of the same duration as that of the evoking stimulus, which in the above mentioned example is 40 ms. The FFR is often analysed using an Fast Fourier Transformation (FFT) to evaluate the energy contained in the regions corresponding to the fundamental frequency of the stimulus and its harmonics. Typically, FFR is analysed to find out the strength of the F0 and the subsequent two higher formants, F1 and F2. Overall, it can be concluded that the transient portion of the brainstem response is assumed to be the neural correlate of rapid temporal changes inherent in the consonant portion, whereas, the sustained portion can be considered to encode the information related to the periodicity of the fundamental and the harmonics.

1.6 Speech evoked ABR in noise:

It evident from literature that fundamental frequency is the psychophysical correlate of the sensation of pitch of a particular stimulus. On similar lines, it has also been thought that the FFR can yield information regarding neural processes involved in the process of pitch perception. An extension of this notion would be that the FFR can also be used to assess the ability to encode information related to pitch in the presence of noise. This can be considered as the neural correlate of the speech perception in noise as it is believed that the strength of F0 perception is a predominant factor associated with perception of speech in noise.

There have been many studies to understand the effects of noise on the speech evoked ABRs. Russo, Nicol, Musacchia, and Kraus (2004) evaluated the speech evoked brainstem responses in 32 children with normal hearing, in quiet as well as in the presence of noise. They found that the addition of background noise significantly altered the brainstem encoding of the syllable /da/. It was observed that the onset responses V and A were the most affected (in 40% of the subjects) whereas the FFR portion remained relatively stable. They reported that, for the V-A complex the amplitudes were significantly reduced and latencies were significantly delayed, whereas for the FFR portion the latencies were fairly preserved and the amplitudes of the different peaks were significantly delayed. They also reported that the strength of F0 and F1 were significantly reduced in the presence of noise in comparison with the normal condition. However, they showed that responses were stable across repeated recordings wherein most of the parameters of the responses were found to have statistically good test-retest reliability.

Cunningham, Nicol, King, Zecker, & Kraus (2002) recorded ABRs to the syllable /da/ to determine the effect of noise on the neural encoding of specific speech features. They compared the responses in quiet and in presence of noise for the amplitude of the onset response, formant transition, and steady state response segments. Results indicated background noise significantly reduced the amplitude of onset portion. The reduction was seen to be greatest for the onset portion. Formant transition showed the next greatest reduction in amplitudes (greater than the vowel portion) when the responses were compared between quiet and noise conditions. Overall, they reported that the effect of noise was greatest for the release burst information encoded by the stimulus onset, and smallest for the vowel portion encoded by the steady state FFR.

Song, Skoe, Banai and Kraus (2011) measured the correlation between behavioural speech perception in noise and the neural encoding of the syllable /da/ in the presence of multi-talker babble in 17 participants with normal hearing and no musical background. They found that background noise diminished the amplitudes of F0 in all their participants. This effect was much more evident in individuals who scored poorly on the behavioural QuickSIN test. They also reported significant correlation between the behavioural QuickSIN scores and the amplitudes of F0. They concluded that these findings suggest that sub cortical representation of the F0 plays a role in perception of speech in noisy conditions.

Though there are many studies to show the effects of noise on speech evoked ABRs, there is scanty information regarding this phenomenon in individuals with cochlear hearing loss. Plyler and Krishnan (2001) investigated FFR in normal and individuals with hearing impairment to observe if there was any degradation in the neural encoding of second formant transition of a synthetic stop consonant as a consequence of hearing impairment. They recorded FFRs for a 15-step /ba/-/da/-/ga/ continuum generated by varying the onset frequency of the second formant transition from 900 to 2300 Hz. Their results indicated that the encoding of the FFRs was severely degraded for the individuals with hearing impairment. They also reported that the degradation in FFR encoding correlated positively with the behavioural perception.

Sumesh and Barman (2008) recorded speech evoked ABRs in individuals with normal hearing and those with sensori-neural hearing loss. They reported that the ABRs were significantly affected in the hearing impaired-groups in comparison with the normal hearing group. This effect was seen with respect to both the amplitude and latencies of the speech evoked brainstem responses. The amplitude and latencies of the onset portion of the ABR was seen to be most affected whereas the FFR portion remained relatively stable with respect to the latencies. However, the amplitudes of the peaks of the FFR portion were significantly reduced in the hearing impaired-group in comparison to the normal hearing group. The same finding was seen when they compared the strengths of the encoding of the F0 and F1 i.e., hearing impairment significantly reduced the strength of encoding of both F0 and F1. They further observed that the degree of hearing loss correlated significantly with the degree of deterioration of the analysed ABR component. They concluded that even when similar levels of speech were presented for both normal and hearing impaired, there was some degradation in the encoding of each of the parameters of speech which were evidenced in the relatively poorer latency and amplitude measures.

Kumar and Maruthy (2011) observed the effects of hearing impairment in individuals with mild to moderate sensori-neural hearing impairment on brainstem encoding of the syllable /da/. In comparison with individuals with normal hearing, they reported that the mean latencies and amplitude of the ABR components were different in the impaired group. However, there was no significant difference in the encoding strength of F0 between both the groups, but was significantly poorer in SNHL group for the encoding of first formant frequency (F1).

Based on the limited number of studies mentioned above on the effect of hearing loss on encoding of speech stimuli at the brainstem, it can be deduced that hearing loss tends to worsen the neural representation of speech.

1.7 Overcoming the effects of hearing loss:

Overcoming the deficits of audition as a consequence of hearing loss has been widely investigated for long. The simplest method to overcome the effects of hearing loss is to provide the individuals with hearing impairment an amplification device. The rationale behind providing simple amplification was to facilitate perception of speech which is reduced as a consequence of reduced audibility of the different features of speech, and that improving audibility will result in improvement of speech perception in individuals with hearing impairment. However, over the years, it has become clear that a simple increase in audibility alone is not sufficient to overcome the deficits caused by hearing loss. Hence, many strategies have been incorporated into the hearing aid technology to enhance speech perception. These include the use of compression circuits, multi-microphone system, noise reduction strategies etc. However, it has to be noted that, no hearing aid with even the most sophisticated of technologies can completely recapture the efficiency of the natural hearing/ear.

Many studies have documented the effects of amplification on perception of speech. Schwartz, Surr, Montgomery, Prosek and Walden (1979) used California Consonant test to measure the aided and unaided speech perception scores in individuals with sensori-neural hearing loss. They reported that there was a significant improvement in the speech discrimination scores in the aided condition in comparison with the unaided condition for the perception of CVC monosyllabic words. Duquesnoy and Plomp (1983) studied the effect of hearing aid on speech reception thresholds for conversational sentences in 50 subjects with hearing impairment. They reported significant improvements in the speech recognition thresholds in the aided condition in comparison to the unaided condition.

Similarly, a vast number of published studies have reported that hearing aid improves the perception of speech in individuals with hearing impairment. Many techniques have been used to enhance speech perception through hearing aids. The use of digital hearing aids in the recent years has further enhanced the possibility of near normal perception by the hearing-impaired, even in adverse listening conditions like in the presence of noise, reverberant rooms etc. Hence, it can be emphatically concluded that the hearing aid use benefits the users in a variety of listening environments.

1.8 Monaural versus binaural amplification:

Over the years, significant time and interest has been devoted towards understanding the benefits of binaural hearing over monaural hearing, as well as regarding binaural amplification. Both individuals with normal hearing as well as those with hearing impairment have been studied in great detail to observe the differences in hearing through binaural versus monaural mode. Not only does binaural hearing result in better localization, it also aids in better perception of speech (both in quiet and noise), better sound quality and timbre and also higher naturalness and overall consumer satisfaction. The same has been observed in individuals with hearing impairment as well.

Many studies have observed the differences between binaural and monaural amplification. Although there are a few studies that have suggested monaural amplification is either sufficient or the amplification of choice, most recent studies have advocated the use of binaural hearing aids against monaural hearing aid fitting.

Dirks and Wilson (1969) evaluated the monaural and binaural hearing abilities of three individuals with sensori-neural hearing loss in aided and unaided conditions. They observed that there were significant benefits in using binaural hearing in comparison with the monaural hearing, in both aided and unaided conditions. However, they also observed that such superiority of binaural hearing was present only when the target stimulus and the competing message were either from different sources or had interaural disparities with respect to time of arrival and not when they were presented from the same general (direction of the) source or simultaneously.

Nabelek and Pickett (1974) examined the perception of speech in monaural and binaural aided conditions in individuals with normal hearing and individuals with sensori-neural hearing losses. They also compared the perception scores in noise and reverberation conditions and reported that the speech perception scores for binaural hearing were consistently better than monaural scores in all hearing-impaired individuals across all conditions of noise and reverberation.

Numerous studies have revealed significant binaural advantage in individuals with sensori-neural hearing loss, over a large variety of listening environments. Additionally, advancements in the hearing aid technologies like the use of noise reduction strategies, multiple channels, multi-microphone systems, either alone or in combination with each other, have enhanced the possibilities of obtaining maximum benefits from binaural hearing aid fitting.

1.8 Issues in aiding asymmetric hearing loss

From the previous section on binaural amplification, it can be construed that binaural hearing aid fitting has distinct advantages over monaural fitting. However, many scholars have suggested few eligibility or selection criteria for the fitting of binaural hearing aids. The most important among the factors that govern binaural amplification is the symmetry of hearing loss. There is great variability in most aspects related to asymmetric hearing loss, starting from the definition of asymmetric hearing loss to the benefits (or the lack of it) of binaural hearing aids in individuals with asymmetric hearing loss. Since most researchers adopt a functional definition of what they consider as asymmetric hearing loss, in the present study, an individual is considered to have asymmetric SNHL if there is a difference in the pure-tone average of greater than 15 dB in at least two successive frequencies.

Since the pure-tone thresholds across the two ears are varying, the task of fitting individuals with such type of hearing losses with binaural hearing aids is a tricky one. This is because, not only are their thresholds are different, but also their psychoacoustic characteristics at supra-threshold levels. Therefore, there is great variability in the opinions regarding the efficacy of binaural amplification in individuals with asymmetric hearing loss. There are published reports which show significant benefits of binaural amplification in asymmetrical hearing loss as well as decrease in speech perception abilities.

Markides (1977) reported the binaural advantages in 12 individuals with cochlear hearing loss. He observed that the mean aided binaural scores were significantly superior to their monaural counterparts, at all SNRs employed. He also reported the squelch effect (2.46 dB) and the head shadow effect (7.36 dB) were significantly higher than the monaural condition at all SNRs. Furthermore, a superiority of binaural amplification was present even when the stimuli were presented from the side of the poorer ear. He concluded that the use of binaural amplification is beneficial even in individuals with asymmetric hearing loss. Similar binaural advantages in speech perception as well as localization have been reported by MacKeith and Coles (1971), Byrne and Dermody (1975) and others.

Nabelek and Mason (1981) compared the word identification abilities for binaural and monaural conditions in individuals with various degrees of hearing loss and audiometric configurations. They compared the difference between the benefits of binaural amplification for symmetric and asymmetric SNHL as a function of noise and reverberation. They observed that the deleterious effects of noise and reverberation were significantly greater for subjects with asymmetrical audiometric thresholds in comparison to the individuals with symmetric hearing loss. The same results were obtained for both aided and unaided conditions. They concluded that the use of binaural hearing aids in individuals with asymmetric hearing loss should be considered with care, especially when their listening environments are challenging. Davis and Haggard (1982) also reported decreased speech recognition, especially in the presence of noise, for those having asymmetrical hearing losses when fitted with binaural amplification.

Many reasons and hypotheses have been put forth for the failure of binaural amplification in asymmetrical hearing loss. It is supposed that the asymmetry in the thresholds leads to interference in the perceived sounds, leading to distorted perception of speech. This may be due to the differences in the arrival of signal at the different levels of auditory system that are associated with the processing of binaural information. Such differences may lead to muffled perception of speech, diplacusis etc. Another probable explanation for the lack of benefit from binaural amplification in individuals with asymmetric hearing loss is the presence of significant interaction and integration problems at the central auditory system. Such deficits are generally encountered in the elderly (Gatehouse and Haggard, 1982). Therefore it is suggested to exercise caution while prescribing binaural hearing aids to asymmetric hearing loss individuals.

Need for the study

Ostler, Rucker and Crandell (2001) reported that individuals with asymmetric sensori-neural hearing losses (SNHL) had poorer speech identification scores in the presence of noise compared to individuals with symmetric SNHL. The same was also reported by Bronkhorst and Plomp (1989). Dillon (2001) and Markides (1982, 1986) attribute this to the phenomenon of diplacusis in which, a person hears a different pitch in each ear which would cause binaural interference leading to the binaural speech identification scores being poorer than monaural scores in individuals with asymmetric hearing loss. However, encoding of the fundamental frequency and its relation to speech perception in noise in individuals with symmetric and asymmetric hearing loss has not been systematically studied. Hence, it is important to systematically study the coding of fundamental frequency in individuals with symmetric and asymmetric SNHL.

The neural encoding of fundamental frequency can be analyzed fairly accurately using the speech evoked auditory brainstem responses (Skoe & Kraus, 2010). The speech perception abilities in the presence of noise have been correlated with poor neural encoding of the fundamental frequency in individuals with learning disability (Chandrasekaran et al, 2009). However, there is a dearth of literature regarding the neurophysiologic bases for speech perception in noise in individuals with cochlear hearing losses. Hence, it is important to understand the electrophysiological correlates of speech perception in noise in such individuals.

There have been many hypotheses and studies that have observed inefficient pitch perception in individuals with SNHL. There are even reports of diplacusis or the perception of two frequencies in individuals with cochlear hearing loss, particularly asymmetric hearing loss. Hence, it becomes essential to study if there is a “diplacusic” encoding of pitch at the neural level in individuals with symmetric and asymmetric hearing loss and also to compare if there is any difference in the neural encoding of pitch between the individuals with symmetric and asymmetric hearing loss.

Aims of the study:

The aims of the present study were

1. To evaluate the speech perception abilities, in quiet and in presence of background noise, between symmetric and asymmetric hearing loss,
2. To evaluate the effects of monaural and binaural hearing aid fitting in individuals with symmetric and asymmetric hearing loss,
3. To observe the neural encoding of pitch in individuals with symmetric and asymmetric hearing loss.

Objectives of the current study:

The specific objectives of the current study were

1. To evaluate and compare the speech perception abilities in quiet and in the presence of noise in individuals with symmetric and asymmetric sensori-neural hearing losses.
2. To evaluate and compare monaural and binaural aided speech perception abilities, in quiet and in the presence of noise, in individuals with symmetric and asymmetric sensori-neural hearing losses.
3. To investigate the monaural and binaural pitch encoding mechanism in individuals with symmetric and asymmetric sensori-neural hearing losses using the speech evoked auditory brainstem responses.
4. To observe the effects of monaural and binaural hearing aid fitting in individuals with symmetric and asymmetric hearing losses.
5. To observe the relation between pitch encoding mechanism and speech perception abilities in individuals with symmetric and asymmetric sensori-neural hearing losses.

Chapter 2

Method:

The present study focused on assessing the neural encoding of speech at the brainstem and also to correlate the electrophysiological encoding of fundamental frequency to the behavioral perception of speech.

2.1 Subjects:

A total of 29 subjects, in the age range of 35 - 55 years, participated in the study. The subjects were selected based on the following criteria:

- Pure-tone averages not greater than 65 dB HL in the poorer ear and a minimum of mild degree of hearing loss (> 25 dB HL) in the better ear.
- Elevated Air-conduction and Bone-conduction thresholds, with Air Bone Gap within 10dB HL.
- Speech identification scores proportionate to the degree of hearing loss for cochlear pathology.
- Elevated or absent acoustic reflex thresholds.
- No history of neurological or otological symptoms.
- Auditory Brainstem Responses proportional to the degree of hearing loss, with no indication of retro-cochlear pathology.
- Absent Transient Evoked Oto-acoustic emissions, indicating cochlear hearing loss.

The participants were divided into two groups. The first group, called as the **"Symmetric"** group, consisted of 14 individuals with cochlear hearing losses with less than 10 dB HL difference across the two ears. The second group, called the **"Asymmetric"** group, consisted of 15 individuals with cochlear hearing losses greater than 10 dB HL but lesser than 25 dB difference in at least two frequencies across the two ears (Prasad & Cousins, 2008).

2.2 Instrumentation:

- A 2-channel OB-922 diagnostic audiometer was used to estimate the hearing thresholds for all the participants and also to assess the speech perception abilities, both in quiet and in noise.

- Loudspeakers were arranged such that stimuli were delivered at azimuths of 0°, 90° and 270° in the horizontal plane.

- A calibrated middle ear analyzer GSI-Tympstar was used for tympanometry and reflexometry.

- Auditory brainstem responses were recorded using a Biologic Navigator Pro evoked potential system in the free field condition (using a dB technologies loudspeaker).

- Two hearing aids of the same company were used for each subject to provide binaural amplification. Each subject was given an option of selecting hearing aids from three different companies. The choice of the hearing aid by the subject based on their subjective preference and/or ease of listening because all the subjects performed similarly for all the three pairs of hearing aids chosen (when tested with spondee word list in free field condition)

- NOAH software using a HiPro interface was used to program the hearing aids to the appropriate levels.

- A personal computer with Pratt software (Version 5.1.44) was used to generate the stimulus for electrophysiological recording.

2.3 Stimuli:

- For the behavioral testing, the stimuli used were 20 different nonsense VCV combinations of the different consonants of Kannada language in the vowel environment of /a/. VCVs were selected for the present study as nonsense syllables provide minimum linguistic redundancy. All stimuli were randomized for each set of presentation to avoid order effect. Also, the vowel used for the testing was /a/ because the same vowel (but synthesized) was also used to evaluate the strength of neural encoding of the fundamental. The VCVs were presented live by a male native-speaker of Kannada. The same speaker was used to present the stimuli for all the subjects in all the conditions. The VU-meter was monitored appropriately to avoid over-shooting or under-shooting of the presented live stimuli.
- Speech noise from the audiometer was used as the masker for the behavioral testing.
- For the electrophysiological testing, vowel /a/ was generated using the Vowel Editor tool of the Pratt software (Version 5.1.44). The stimulus was of 100 ms in duration with a fundamental frequency of 100 Hz. It also consisted of subsequent formant energies at 789 Hz (F1), 1300 Hz (F2), 2096 Hz (F3), and 2579 Hz (F4). The stimulus was then resampled at 48000 Hz for use in the Biologic Evoked potential system.

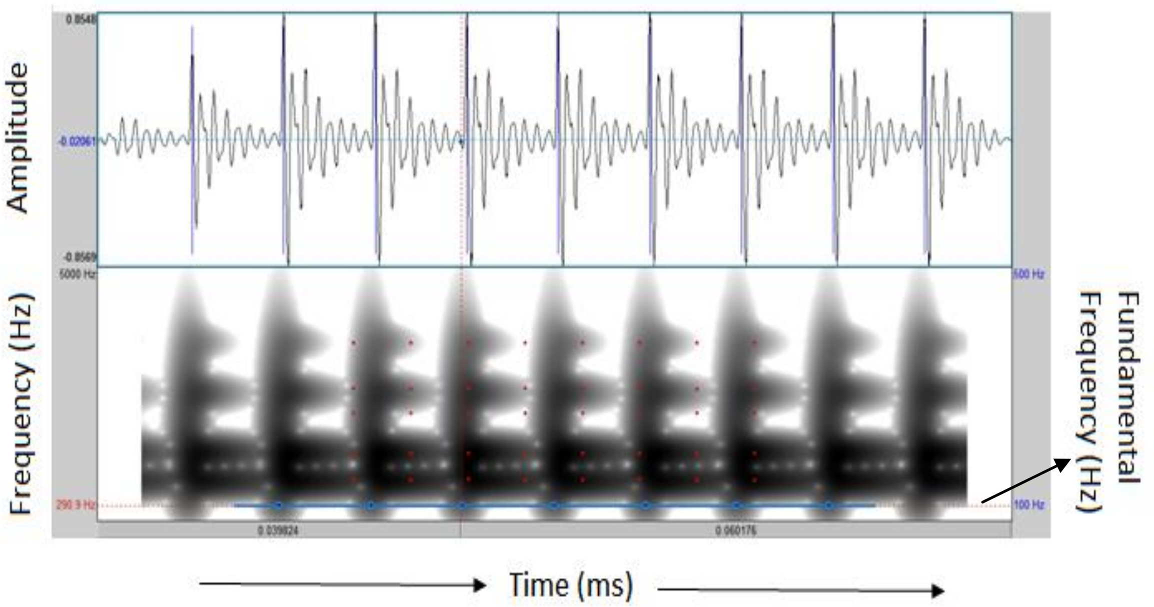

*Figure 2.1.*Spectral, amplitude and temporal parameters of the vowel /a/ used for the present study. In the upper panel, Y-axis represents the amplitude of the stimulus and in the lower panel Y-axis represents the frequency. The X-axis in both the panels indicates the time (in ms). The blue line at the bottom of the lower panel indicates the fundamental frequency of the stimulus

- White noise, in the default setting of the BioMark protocol, was used as masker for the electrophysiological testing.

2.4 Test environment:

All the tests were carried out in well illuminated, air conditioned rooms which were acoustically treated. The noise levels in the test rooms were within the permissible levels as recommended by ANSI S-3.1 (1991).

2.5 Test procedure:

2.5.1 Pure-tone audiometry:

Pure tone air conduction thresholds for each subject were established for octave frequencies from 250 Hz to 8000 Hz using the modified Hughson and Westlake method (Carhart and Jerger, 1959). Bone conduction thresholds were also established using the same method for octave frequencies from 250 Hz to 4000 Hz.

2.5.2 Immittance evaluation, acoustic reflexes and oto-acoustic emission testing:

The tympanometric measurements were done using 226 Hz probe tone of 85 SPL to rule out any middle ear pathologies. For acoustic reflex measurement, reflex eliciting tones of 500, 1000, 2000 and 4000 Hz were presented both ipsilaterally and contralaterally to find out the presence or absence of acoustic reflexes. A significant change in the admittance value of greater than 0.03 ml was considered for the reflexes to be present.

Oto-acoustic emissions were also measured for both the ears for all the participants. TEOAEs were recorded for click stimulus of 80 dB peSPL. OAEs were measured for the frequencies of 500, 1000, 2000 and 4000 Hz. A cut-off SNR of 6 dB above the noise floor was considered for the OAEs to be present.

2.5.4 Behavioral evaluation of speech identification:

Before the commencement of the actual behavioral speech perception test, all the subjects were fitted with binaural hearing aids. Each of these hearing aids was initially programmed according to the audiogram of the respective subject using NOAH software. The following points were taken care of while considering the type of hearing aids selected and while programming the hearing aids;

- ✓ The hearing aids chosen for the present study were 4-channel hearing aids which were generally prescribed for individuals with hearing losses lesser than moderately severe degree.

- ✓ Electro acoustic characteristics of each of the hearing aids were measured and found to be within acceptable limits (Equivalent input noise, various types of distortions etc).

- ✓ Initial fitting based on the audiogram was done using NAL-NL1 as the prescriptive formula. Further, fine tuning was done to make sure the gain set in the hearing aid was appropriate for the subject being tested i.e., a preferred gain was considered as the gain setting of choice instead of the prescribed gain (as provided by the prescriptive formula). The fine tuning involved adjusting the gain parameters across the four channels such that the audibility and hence the speech perception was optimal.

- ✓ The hearing aids were programmed such that they functioned in the linear mode i.e., the (amount of) compression in each of the hearing aids was set to zero. Also, it was ensured that the output levels of the stimuli used for the testing did not cross the UCLs of the subjects.

- ✓ The number of programs set into the hearing aids was limited to the most basic settings i.e., only one program was used.

- ✓ All other special features like feedback suppression, noise reduction algorithms, data logging etc. were turned off. The intention of such an exercise was to ensure that there was no unintended delay introduced into the output of the hearing aids when such features are kept turned on, there by changing the time (latency) related information at the brainstem.

Behavioral identification of VCV syllables were carried out on all the participants by presenting them through loudspeakers placed at different azimuths. The azimuths selected were 0°, 90°, and 270° in the horizontal plane. 0° was used to evaluate a true binaural hearing condition, whereas 90° and 270° azimuths were used to evaluate the identification scores in the monaural conditions. Speech identification testing was done under two main categories – unaided and aided. In the unaided condition, the scores were evaluated in quiet as well as in the presence of speech noise (0 dB SNR). In both of these conditions, speech identification scores were measured for binaural, predominantly monaural left (M_L) and predominantly monaural right (M_R) conditions. The term predominantly monaural is used because, the loud speaker was kept right in front of the ear to be tested (i.e., in front of right ear for 90° and in front of left ear for 270°), but the contra lateral ear was left unmasked and unoccluded. Such a set up was created to allow a more natural (monaural) listening condition rather than a laboratory (unilateral) condition. The same set-up was preserved for the aided condition as well.

The participants were asked to repeat a list of 20 VCV syllables for each of the 12 conditions thus arose. The order of presentation of the stimuli for each of the conditions was randomized to avoid any order effect. In all the conditions, the speech material was presented at 45 dB HL which was found to be the most comfortable level for normal hearing individuals as observed in a pilot study conducted on 10 normal hearing individuals. The same level was also selected for testing the individuals with cochlear hearing impairment in order to simulate a more natural conversation level. For the binaural testing condition, VCV syllables were presented through the loud speakers placed at 0° azimuth. Same condition was kept for aided vs. unaided testing, both in quiet as well as noise conditions. For the predominantly monaural right (M_R) condition, the speech was routed through the loudspeaker placed at 90° azimuth in the horizontal plane, i.e., kept in front of the right ear. The other ear was kept unoccluded and unmasked in order to simulate a more natural monaural listening condition rather than a laboratory condition. Again, the same setting was kept for aided vs. unaided testing, in both quiet and in the presence of ipsilateral speech noise. Similarly, for the predominantly monaural left (M_L) condition, speech identification was tested by routing the speech through the loudspeaker placed at an azimuth of 270° in the horizontal plane i.e., in front of the left ear. Similar to the right ear testing, the contra lateral ear was kept unoccluded and unmasked. In all these conditions, the number of syllables identified correctly was calculated in order to assess the speech perception abilities.

2.5.4 Electrophysiological assessment:

For the electrophysiological assessment, all the participants were comfortably seated on a reclining chair in an electrically and acoustically treated room. The participants were made to watch a captioned movie with volume turned low. Brainstem responses to speech stimulus /a/ were recorded for all the participants by presenting the stimulus through loudspeakers. The Speech evoked ABRs were recorded for the same conditions as mentioned in the behavioral testing phase - binaural, predominantly right monaural (M_R) and predominantly left monaural (M_L), with the same loudspeaker placement. For the unaided testing, the stimulus was presented at 85 dB SPL with the subject being placed 1-meter away from the speaker. However, the aided testing was carried out by presenting the stimulus at 65 dB SPL. It was ensured that the presentation level of the stimulus was at the most comfortable level (MCL) for all the subjects considered in each of the conditions. Also, the hearing aid selected for the behavioral testing was used for the electrophysiological testing. It was also made sure that the characteristics of the hearing aid were the same for both the behavioral and electrophysiological testing. The protocol for recording speech evoked ABRs are as presented in Table 2.1.

Table 2.1:

Test protocol for acquisition of speech evoked ABR.

Acquisition Parameters	
Montage	Inverting: Nape of the neck Non-inverting: C_z Ground: F_{pz}
Filter	HPF: 80 Hz LPF: 2000 Hz
Analysis epoch	170.67 (-30 ms prestimulus)
Artifact rejection	23.8µV
Notch filter	On
Amplification	1,00,000
Sweeps	1500
Stimulus Parameters	
Transducer	Loud speaker (dB technologies inc.)
Stimulus	/a/ (100ms duration)
Polarity	Alternate
Intensity	85 dB SPL for unaided testing 65 dB SPL for aided testing
Stimulation rate	5.3/s

Chapter 3

Results and discussions:

The present study was aimed at understanding the encoding of fundamental frequency in individuals with symmetric and asymmetric cochlear hearing losses. It was also aimed at understanding the correlations between the strength of neural encoding of fundamental frequency and the behavioral perception of speech, both in quiet and in the presence of background noise. Hence the results will be discussed separately for the behavioral and the electrophysiological tests. For the statistical analyses, the behavioral speech perception scores and the electrophysiological parameters were considered as the dependent variables whereas the different conditions and the sub-conditions i.e., condition (quiet and noise), hearing aid (aided and unaided) and ear (predominantly right, predominantly left and binaural) as well the two groups (symmetric and asymmetric hearing loss) were the independent variables.

3.1 Behavioral

Statistical analyses were done using SPSS (Version 18) software to compare the behavioral scores of the asymmetric and symmetric groups, across the different condition (quiet and noise), hearing aid (aided and unaided) and ear (right, left and binaural).Mixed ANOVA (repeated measure ANOVA for condition, hearing aid and ear, with group as independent factor) revealed that there was no group effect for any of the conditions considered, indicating that there was no statistically significant difference between the symmetric and asymmetric group in any of the conditions tested. This indicates that the performance of both the groups on the behavioral speech identification task was comparable. However, it can be noted from figure 3.1 that the mean behavioral scores for the symmetrical group were greater than asymmetrical group for all the conditions but the difference did not reach statistical significance.

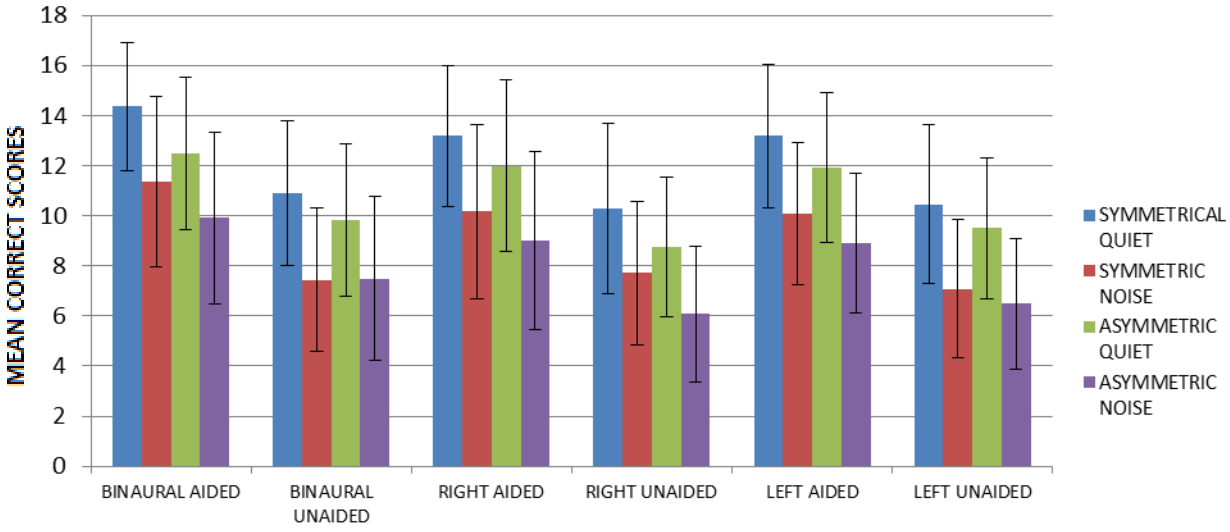

*Figure 3.1.*Mean and Standard deviations of behavioral speech perception scores for both symmetric and asymmetric groups across different conditions – comparison of binaural versus right versus left.

Mixed ANOVA was administered on the data and it indicated that there was significant ear effect (F (2, 42) = 6.664, $p<0.01$), hearing aid effect (F (1, 21) = 158.395, $p<0.001$) and condition effect (F (1, 21) = 389.731, $P<0.001$). However, there were no significant interaction effects.

Hence it can be concluded from mixed ANOVA that, the behavioral scores for aided conditions were significantly higher than unaided, quiet conditions better than noise. Also, since there was significant ear effect, Bonferroni's adjusted comparison was used as the post-hoc analysis. It showed that there were significant differences between binaural and predominantly right (M_R) ($p<0.05$) as well as binaural and predominantly left conditions (M_L) ($p<0.05$), but there was no statistically significant difference between the scores obtained for M_L and M_R conditions.

In the above analyses, the binaural data were compared against individual scores of right and left ear taken separately. In order to get a better understanding of monaural versus binaural differences, the means of the M_L and M_R scores were obtained for each subject, across all the conditions and they were further compared against the corresponding binaural scores. Mixed ANOVA for the binaural and monaural scores also revealed no significant group effect. However, it was also observed that there was no significant difference between conditions considered. Again, it was noted that the mean scores for the symmetrical group were greater than asymmetrical group for all the conditions.

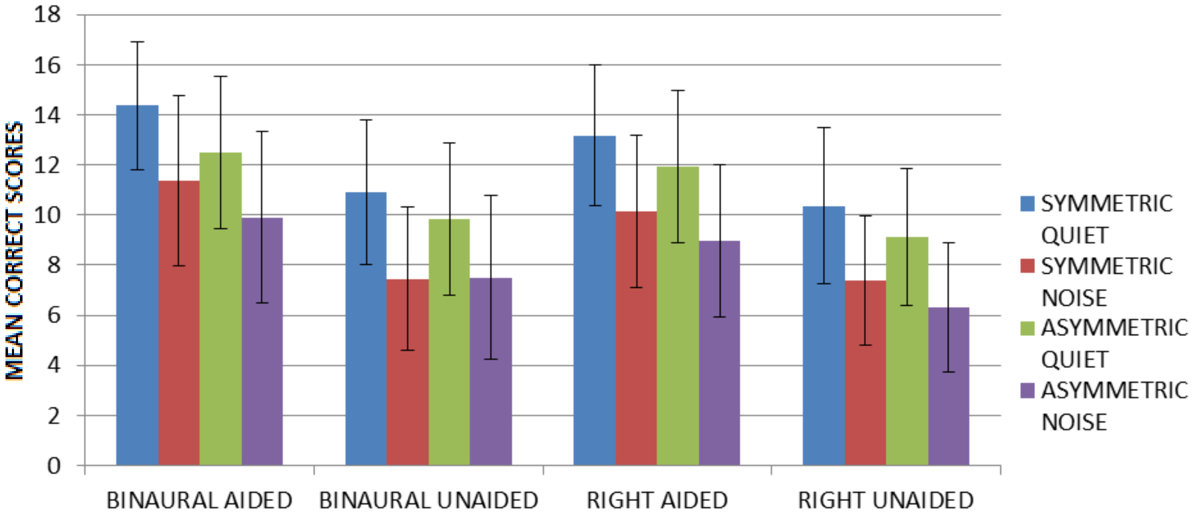

*Figure 3.2.*Mean and Standard deviations of behavioral speech perception scores for both symmetric and asymmetric groups across different conditions – comparison of monaural versus binaural.

Hence the following can be concluded from the analyses of behavioral speech perception scores

- The speech perception abilities of both the symmetric and asymmetric groups are comparable,
- Behavioral speech perception in the binaural conditions is better than either left or right ear, taken separately,
- Quiet conditions are better than noise conditions,
- Aided conditions are better than unaided conditions,

- The above three results are same for both symmetric as well as asymmetric groups.

There have been mixed reports about the speech identification performances in individuals with symmetric and asymmetric hearing losses. Few studies have reported clear superiority of the hearing symmetry in speech recognition tasks compared to asymmetry of hearing, while other studies have reported that there is no statistically significant difference between symmetric and asymmetric hearing losses, especially when the loudness/summation is maintained at appropriate levels across both the ears.

Davis and Haggard (1982) suggested that hearing asymmetries of up to 10 dB is acceptable for binaural hearing aid fitting, indicating that at lower degrees of asymmetry, there is less negative interaction of the poorer ear with the better ear. Results of their study indicate that there was no statistically significant difference in the speech identification scores of symmetric and asymmetric groups when the asymmetry is lesser than 10 dB across the ears. However, as the asymmetry increased to 15 dB and greater, the individuals with symmetric hearing loss performed significantly better. This was more pronounced in the aided conditions of quiet as well as in the presence of noise. In the present study, however, it was observed that there was no significant difference between the symmetric and asymmetric groups, even when the criterion for asymmetry was considered as a minimum difference of 15 dB across the ears. One possibility for this result is the small sample size (14 symmetric and 15 asymmetric). A larger number might have yielded a significant difference between the two groups by reducing the variance.

Arkebauer, Mencher and McCall (1971), in their study which compared the performance of individuals with symmetric and asymmetric hearing losses, reported that asymmetric hearing loss has clear deleterious effects in binaural hearing, and especially in binaural amplification. They suggested that there were detrimental interactions of the poorer ear on the better ear when binaural performance was considered. Jerger, Silman, Lew, and Chmiel (1993) also reported similar negative interactions by the worse ear when binaural hearing was being tested.

However, Ostler, Rucker and Crandell (2001) reported that, in 16 subjects each with symmetric and asymmetric hearing losses, individuals with mild to moderate sloping asymmetrical hearing losses perform on par with individuals with equal amount of symmetric hearing losses when their speech perception ability was tested. They also reported that, the performance remained similar as long as the target speech was not presented directly to the poorer ear. They further reported, however, that the individuals with asymmetric SNHL exhibited greater difficulty in understanding speech in the presence of background noise than the individuals with symmetric hearing losses, if the speech signals were presented to the poorer ear. These results by Ostler and others are in consonance with the results of the present study that there was no significant difference between the symmetric and asymmetric groups. But, it has to be noted that in the present study the results were not analyzed keeping in mind the poorer or better ear, and only right and left ear means were considered, irrespective of the fact that they might be the poorer or better ear in a particular individual.

Dirks and Wilson (1969) demonstrated that, in the presence of background noise, binaural hearing was consistently superior to monaural hearing when they considered the speech perception abilities of individuals with symmetric mild to moderate SNHL. Similar findings are also found in the present study where binaural hearing has been found to be better than monaural scores. It can also be observed from the above studies that the perception of speech in the presence of noise is significantly poorer than perception in quiet conditions, as observed in the present study.

3.2 Electrophysiology

3.2.1 Fundamental frequency

Statistical analysis was done to compare the frequency of the F0 as encoded at the brainstem. The frequency F0 was analyzed for each subject across each condition using a custom designed MATLAB FFT program (Gnanateja, 2013). Mixed ANOVA revealed no significant differences in the frequency of the F0 between both the groups. Even within the groups, there was no significant difference between the different conditions in terms of the frequency of the encoded F0. Additionally, even when the right and left scores were combined to give individual monaural scores, the statistical analysis failed to show a significant group effect or significant differences between any of the conditions. Thus it was concluded that there was no significant effect of symmetric or asymmetric hearing loss, quiet or noise conditions, aided or unaided conditions, as well as monaural, binaural, M_R or M_L ear conditions.

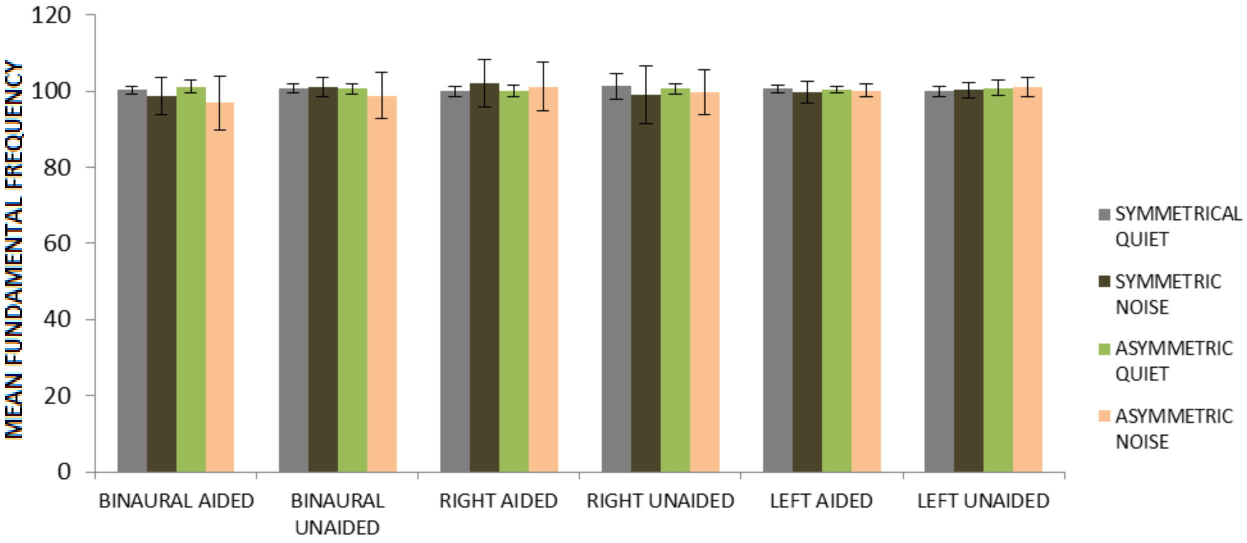

*Figure 3.3.*Mean and Standard deviations of electrophysiological fundamental frequency (as analyzed using FFT) for both symmetric and asymmetric groups across different conditions – comparison of binaural versus right versus left.

Such tolerances of the brainstem to noise have been demonstrated in previously reported studies, where it is observed that the fundamental frequency (or the pitch) of the stimulus was largely preserved when the response spectrograms were analyzed using FFT. Li and Jeng (2011) have reported that the steady state portion of the speech evoked ABR remained stable till the SNR was degraded to 0 dB. Similar results have also been reported by Russo et al. (2004), Song, Skoe, Banai, and Kraus (2011), and several other researchers, where they have used the syllable /*da*/ and obtained relatively preserved pitch coding for SNRs as low as 5 dB.

3.2.2 Amplitude of F0

Similar to the frequency of fundamental, the amplitude/strength of encoding of fundamental frequency was also determined using the MATLAB code. The amplitude was obtained at the stimulus-F0 of 100 Hz for all the conditions for both the groups. Mixed ANOVA revealed no statistically significant group effect in terms of the amplitude of the encoding of F0 indicating that there was no significant difference in the strength of F0 encoding between the symmetrical and asymmetrical group. However, it can be observed from table 3.4 that the mean scores for the symmetric group were higher than the asymmetric group in all conditions.

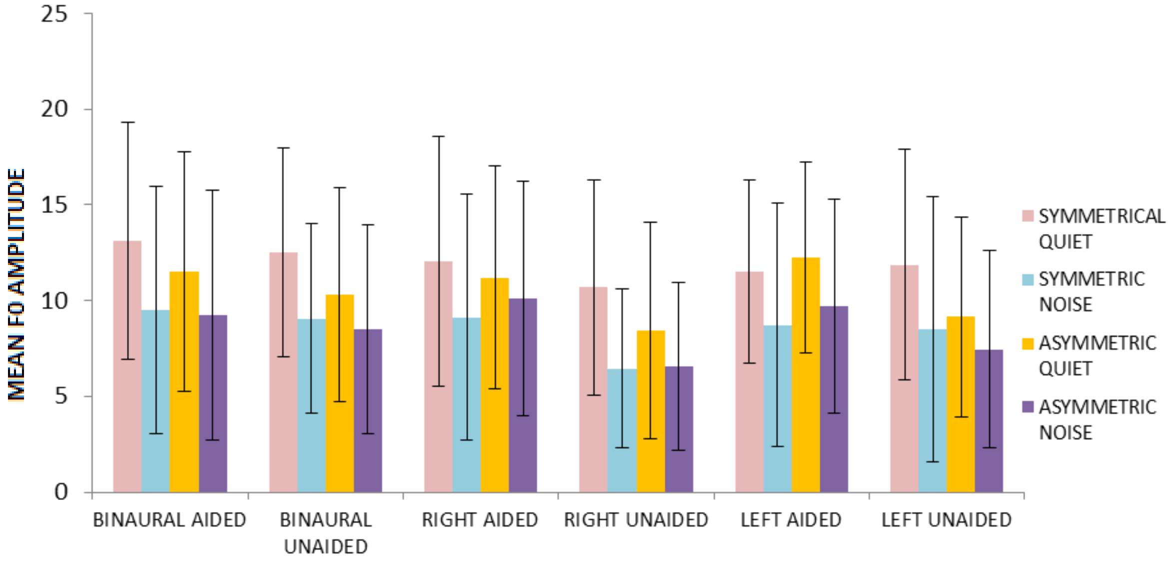

*Figure 3.4.*Mean and Standard deviations of amplitudes of F0 (as analyzed using FFT) for both symmetric and asymmetric groups across different conditions – comparison of M_R versus $M_L$versus binaural.

Although there were no significant differences between the symmetric and asymmetric group, there were statistically significant differences observed among the different conditions when they were compared within each of the groups. There was no significant difference between the binaural and the two monaural conditions (binaural versus M_L versus M_R, F= 1.67, p>0.5). But there were statistically significant differences between the hearing aid conditions (aided versus unaided, F=8.568, P<0.005) and the quiet versus noise conditions (P<0.005). No statistically significant interactions were observed for any combination of the different conditions except when all three conditions were considered, as can be observed from table 3.1.

Table 3.1.

Degrees of freedom, F value and statistical significance of interaction across different conditions for the F0 amplitudes.

Interactions	**df**	**F**	**Sig.**
EAR * GROUP	2,42	0.12	0.88
HA * GROUP	1,21	1.90	0.18
COND * GROUP	1,21	2.80	0.10
EAR * HA	2,42	0.94	0.39
EAR * HA * GROUP	2,42	0.36	0.69
EAR * COND	2,42	0.07	0.92
EAR * COND * GROUP	2,42	0.32	0.72
HA * COND	1,21	0.56	0.46
HA * COND * GROUP	1,21	1.83	0.19
EAR * HA * COND	2,42	3.70	0.03*
EAR * HA * COND * GROUP	2,42	0.54	0.58

Since mixed ANOVA showed significant interactions between ear, hearing aid and conditions, further analyses were carried out. In order to compare the differences between the different conditions within the groups, paired samples t-test was done for both the symmetric and asymmetric groups separately. In the symmetric group, it was observed that there were statistically significant differences between quiet versus noise comparisons for both aided versus unaided conditions as well the ear conditions (binaural versus right versus left). This indicates that the strength of F0 encoding was significantly higher for the binaural aided quiet condition in comparison with binaural aided noise condition ($P<0.01$). Similarly, the F0 amplitude was significantly higher for binaural unaided quiet than binaural unaided noise ($P<0.05$), right aided quiet higher than right aided noise ($P<0.01$), right unaided quiet higher than right unaided noise ($P<0.01$). From these comparisons, it can be concluded that the quiet condition revealed significantly stronger encoding of F0 in comparison with the noise condition.

However, statistical analysis did not reveal any significant differences between the aided and the unaided conditions for any of the combinations. This indicates that the strength of encoding of F0 in individuals with symmetric hearing loss was similar for both aided and unaided conditions. Again, it can be observed that although there were no statistical differences observed, the mean F0 amplitude scores were higher for the aided conditions than the unaided conditions.

Table 3.2.

Pair wise comparisons of different conditions of the F0 amplitudes for the symmetric hearing loss group.

Pair	**Ear**	**Comparison**	**t (10)**	**Significance (2-tailed)**
Pair 1	Binaural	Aided quiet – Aided noise	3.34	0.007**
Pair 2		Unaided quiet – Unaided noise	2.82	0.018*
Pair 3	Right	Aided quiet – Aided noise	3.74	0.004**
Pair 4		Unaided quiet – Unaided noise	5.21	0.000***
Pair 5	Left	Aided quiet – Aided noise	1.78	0.105
Pair 6		Unaided quiet – Unaided noise	2.05	0.067
Pair 7	Binaural	Aided quiet – Unaided quiet	0.50	0.622
Pair 8		Aided noise – Unaided noise	0.28	0.785
Pair 9	Right	Aided quiet – Unaided quiet	0.85	0.414
Pair 10		Aided noise – Unaided noise	1.58	0.143
Pair 11	Left	Aided quiet – Unaided quiet	-0.40	0.694
Pair 12		Aided noise – Unaided noise	0.28	0.783

*=p<0.05
** = p <0.01
***=p <0.001

Similarly, in the asymmetric group the same results were obtained. It was observed that there were statistically significant differences between aided quiet versus noise comparisons for both aided versus unaided conditions as well the ear conditions (binaural versus right versus left). Additionally, there were no statistically significant differences for the aided versus unaided comparisons for both ear conditions as well as quiet versus noise conditions. Also, it was observed that there was no significant difference between the binaural versus right or left comparisons. Hence it can be concluded that for the asymmetric group, there was significant improvement in the encoding of F0 for the quiet condition in comparison with the noise condition. However, the strength of F0 encoding was similar for the aided and unaided condition, as well as binaural and monaural conditions.

Table 3.3.

Pair wise comparisons of interaction across different conditions of the F0 amplitudes.

Pair	**Ear**	**Comparison**	**t (11)**	**Significance (2-tailed)**
Pair 1	Binaural	Aided quiet – Aided noise	5.87	0.000**
Pair 2		Unaided quiet – Unaided noise	3.49	0.005**
Pair 3	Right	Aided quiet – Aided noise	5.13	0.000***
Pair 4		Unaided quiet – Unaided noise	3.05	0.011*
Pair 5	Left	Aided quiet – Aided noise	4.81	0.001**
Pair 6		Unaided quiet – Unaided noise	2.73	0.019*
Pair 7	Binaural	Aided quiet – Unaided quiet	0.79	0.441
Pair 8		Aided noise – Unaided noise	0.44	0.667
Pair 9	Right	Aided quiet – Unaided quiet	2.43	0.033*
Pair 10		Aided noise – Unaided noise	2.80	0.017*
Pair 11	Left	Aided quiet – Unaided quiet	2.13	0.056
Pair 12		Aided noise – Unaided noise	1.46	0.172

*=p<0.05
** = p <0.01
***=p <0.001

Again, in an attempt to understand the differences between binaural and monaural encoding of F0, the two monaural (right and left) data were averaged to obtain a single score and this is was further compared with the corresponding binaural scores. Mixed ANOVA for this condition revealed that there was no significant difference between the symmetric and asymmetric groups. Within both the groups, however, there were statistically significant differences for the different conditions. There was no significant ear effect (binaural versus monaural, P>0.5), no significant hearing aid effect (aided versus unaided, P>0.5) whereas a significant condition effect was observed (quiet versus noise, P<0.001). No significant interaction effects were observed for any of the conditions. It was seen that, for the binaural versus monaural comparisons, quiet conditions were significantly higher than noise conditions.

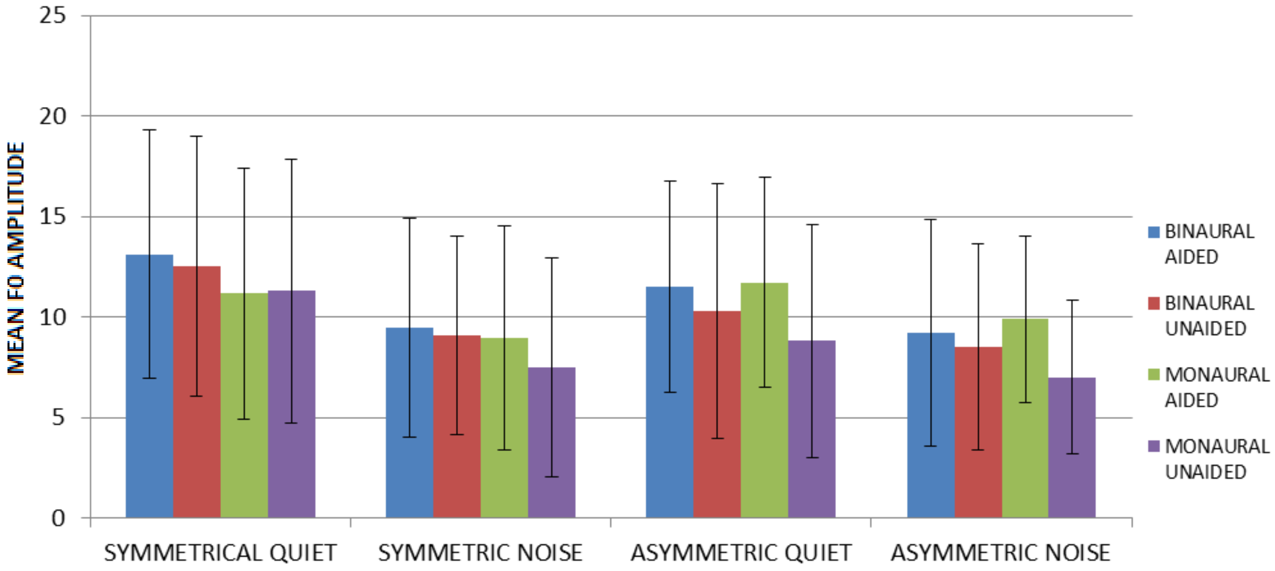

Figure 3.5 Mean and Standard deviations of amplitudes of F0 (as analyzed using FFT) for both symmetric and asymmetric groups across different conditions – comparison of monaural versus binaural.

Furthermore, when paired sample t-test was done for both the groups independently, it revealed that for both the groups there were significant differences between the quiet versus noise comparisons for both monaural and binaural stimulation, but no significant differences between the aided and unaided comparisons for both monaural and binaural stimulation.

Table 3.4.

Pair wise comparison for different conditions of the F0 amplitudes.

Pair	**Ear**	**Comparison**	**t (10)**	**Significance (2-tailed)**
Pair 1	Binaural	Aided quiet – Aided noise	3.34	.007**
Pair 2		Unaided quiet – Unaided noise	2.82	.018*
Pair 3	Monaural	Aided quiet – Aided noise	2.80	.019*
Pair 4		Unaided quiet – Unaided noise	3.79	.004**
Pair 5	Binaural	Aided quiet – Unaided quiet	0.50	.622
Pair 6		Aided noise – Unaided noise	0.28	.785
Pair 7	Monaural	Aided quiet – Unaided quiet	0.47	.647
Pair 8		Aided noise – Unaided noise	1.37	.201
Pair 9	Binaural-Monaural	Aided quiet	1.33	.213
Pair 10		Aided noise	0.38	.709
Pair 11	Binaural-Monaural	Unaided quiet	0.94	.368
Pair 12		Unaided noise	0.99	.342

*=p<0.05
** = p <0.01
***=p <0.001

Hence it can be concluded overall that there are no significant differences between symmetric and asymmetric hearing losses for any of the combinations. However, within each of the groups, the quiet condition resulted in enhanced encoding of F0 in comparison to noise condition and aided conditions revealed enhanced F0 encoding compared to the unaided conditions. Also, binaural conditions showed enhanced F0 amplitudes in comparison with both the monaural conditions.

One of the most significant outcomes of the study is the similarity of symmetric and asymmetric hearing loss in terms of the encoding of F0 at the brainstem. There have been no published studies that have reported and compared the electrophysiological encoding of F0 (pitch) in the auditory system in subjects with symmetrical and asymmetrical hearing impairment. Sebastian and Rajalakshmi (2013) observed the binaural interaction component (BIC) in individuals with symmetric and asymmetric hearing impairment. They reported that the BIC, in terms of latency as well as amplitude, was similar across the symmetric as well as asymmetric groups considered. This indicated that brainstem responses obtained for the individuals with symmetric as well as the asymmetric hearing loss had similar waveforms and hence resulted in similar BIC waveforms, which were derived from the ABRs. Similarly, in the present study as well, the brainstem responses obtained for the all conditions were similar across the symmetric and asymmetric groups when compared with their corresponding conditions.

A few assumptions can be made regarding the similarities of ABRs in symmetric and asymmetric hearing loss. Firstly, it can be assumed that the brainstem has the ability to overcome the inter-aural asymmetries in terms of intensities reaching the cochlea, even in asymmetric hearing losses. Jeffress (1948), in his theory to explain binaural perception of sounds, explains that the auditory system has neurological based extractors for the inter-aural cross correlation of signals, along with additional processing at the brainstem to incorporate for the inter-aural intensity differences (IIDs). These additional processing might be assumed to be a factor for the similarity in ABR waves in symmetric and asymmetric hearing losses, wherein, the brainstem structures try to overcome the differences in the interaural intensities leading to better perception of binaurally presented sounds.

Another assumption might be the degree of hearing loss in the subjects considered for the study. All subjects considered had hearing losses less than 60 dB HL. Coats (1978); Coats & Martin (1977); Jerger & Mauldin (1978),reported that the brainstem responses do not undergo significant deterioration as long as the thresholds at 4000 Hz are lesser than 60 dB HL and significantly deteriorates above 60 dB till 90 dB HL, especially above 70 dB HL. This could be another possible reason why there was no significant difference between the asymmetric and asymmetric hearing loss groups.

An extreme case of asymmetric hearing loss is the unilateral hearing loss (UHL), wherein one of the ears has minimal or no hearing while the other ear has (near) normal hearing. Musser (2010) recorded the speech evoked ABRs in individuals with unilateral hearing impairment. In comparison with individuals with normal hearing, the responses obtained in UHL were significantly delayed in latencies (of all major wave components) and reduced in amplitude (of different wave components as well as strength of F0). However, it has to be noted that, in spite of functionally absent hearing in one of the ears, speech evoked ABRs were recorded in all subjects with unilateral hearing loss. This indicates that binaural hearing is possible and can lead to presence of recordable waveforms in even the most extreme cases of asymmetric hearing loss. Hence, the results obtained in the present study that no significant differences in the speech – ABRs can be explained by extrapolating of the study by Musser.

Another significant result of the present study is the significantly enhanced encoding of F0 for the quiet conditions in comparison to the noise conditions, as evidenced by higher amplitudes of F0 for the quiet conditions in comparison with the noise conditions. Many published reports indicate a significant reduction in the strength of F0 encoding in the presence of noise. Russo, Nicol, Musacchia and Kraus (2004) observed, in 38 normal hearing individuals, that the brainstem responses evoked by using the stimulus /da/ were significantly affected when background noise was introduced. They reported that the amplitudes of F0 and subsequent formants, although more resistant to deterioration compared to the wave V-A complex, were significantly reduced in the presence of background noise when compared to the FFRs measured in quiet conditions. Very similar results of reduced F0 amplitudes have been reported by many other authors like Russo, Nicol, Trommer, Zecker, and Kraus (2009) and Russo, Nicol, Zecker, Hayes, and Kraus (2005).

The reasons for the reductions in the encoding strength of F0 have been extensively researched. The representation of F0 at the brainstem is dependent on the timing/phase information provided by the auditory nerve to the higher auditory structures. The representation of F0 at the brainstem requires highly synchronized firing of the auditory structures at a rate corresponding to the F0. However, the introduction of background noise results in reduction in the synchronicity of firing, thus leading to less robust representation of F0 relative to the response in quiet.

The results of the present study also indicated that the strength of F0 encoding for the aided conditions was higher than the unaided conditions. In all conditions, the mean aided F0 amplitude was found to be higher than the unaided scores, however it did not reach level of statistical significance in all conditions. There are very few studies which report about the speech evoked ABRs for listeners with hearing impairment using hearing aids. However, there are other electrophysiological measures that have been used to evaluate the benefits of hearing aid fitting. Aided cortical auditory evoked potentials (CAEP) have been used to study the use of hearing aid in individuals with hearing loss. Korczak, Kurtzberg, and Stapells (2005) have reported that, in individuals with hearing loss, the use of hearing aids resulted in significant improvement in the detection of auditory evoked P1-N1-P2 complex and also significantly higher amplitudes of the complex in comparison with the unaided conditions. Comparable results have also been reported by other researchers like Rapin and Graziani (1967), Tremblay, Billings, Friesen and Souza (2006) and many others.

Similar to CAEPs, aided ABRs have also been used to understand the benefits of hearing aid fitting. Davidson, Wall and Goodman (1990) used ABRs to evaluate the benefits of evoked potentials validate the prescription procedures of hearing aids. They observed that the presences of ABRs were higher and the amplitudes of aided ABRs were significantly higher in comparison to the unaided conditions, indicating that the introduction of hearing aid helps in better synchronous firing of the auditory structures. Similar results have been reported by Beauchaine, Gorga, Reiland, and Larson (1986), Hecox (1983) and many others.

It can be observed from the above studies that the auditory system is sensitive to the amplification of sound, suggesting that hearing aids boost the neural representation of sounds. By extrapolation of these results, it can be hypothesized that the structures responsible for hearing, including those which are essential for the encoding of F0 of speech, are tuned to be responsive for amplified speech, thus leading to enhanced synchrony and representation of F0.

Although it was observed that the amplitudes of F0 were always higher for the aided condition than the unaided, it did not reach statistical significance in few of the combinations. This might be because, when the use of hearing aid is introduced as a factor, there might be complex effects on the speech evoked ABRs. There might be both an improvement in the representation of speech owing to the amplified nature of the stimulus, or a reduction in the representation of the finer aspects of speech like the representation of F0 and harmonics consequent to the addition of distortion at the output of a hearing aid. Kumar and Maruthy (2011) recorded speech evoked ABRs in individuals with SNHL using the /da/ syllable which was recorded at the output of a hearing aid. They observed that the hearing aid output stimulus had undergone modification/deterioration in the spectral parameters relative to the unprocessed (original) stimulus. They reported no significant difference in the amplitude of F0 across the groups (normal vs. hearing impaired) or the stimuli (original vs. hearing aid processed stimulus). However, they reported that the amplitude of first formant (F1) was reduced in the SNHL group compared to the normal group. Also, they observed that the hearing aid processed stimulus resulted in less accurate representation of F1 compared to the original unprocessed stimuli.

The above results indicate that the presence of hearing loss and hearing aid affects the processing of speech at the auditory brainstem. This might be assumed as a reason for the lack of difference in few of the comparisons. The presence of hearing loss and the presentation of stimuli through loud speakers can be considered to result in less than efficient processing of F0, even in the unaided conditions. If the hearing aid is also added into the context, it can be assumed that it will lead to further deterioration of the stimulus at the acoustic level itself, leading to even further reduced accuracy of F0 encoding.

3.3 Correlation between behavioral and electrophysiological measures:

One of the main aims of the present study was to establish a working correlation between the behavioral perception of speech and the neural encoding of speech stimulus at the brainstem level. To this end, the data obtained in the behavioral and electrophysiological phase were analyzed using Pearson's correlation coefficient to observe the degree of correlation between electrophysiological and behavioral data. To observe the degree of correlation, the behavioral speech identification scores in the different conditions were compared with the frequency of F0 as well as the amplitude of F0 for the respective conditions. Here the correlations are discussed separately for the symmetric and asymmetric group.

In the symmetric group, the binaural condition was considered first. Statistical analyses revealed that the behavioral scores had no significant correlation with the frequency of F0 in any of the conditions (aided vs. unaided as well as quiet vs. noise). However, the behavioral scores showed significantly high positive correlation with the amplitude of F0 for all the four conditions. It was observed that there was high correlation between the behavioral scores and the F0 amplitude in the aided quiet condition (0.781), whereas moderate correlation was observed for the aided noise (0.613), unaided quiet (0.679) and unaided noise (0.614) conditions.

When the right ear condition was considered, similar to the binaural scores, there was no significant correlation between the behavioral scores and the frequency of F0 in any of the four conditions. For the F0 amplitude, it was observed that the behavioral scores showed significant correlation with the amplitude of F0 for the aided quiet condition (0.640), unaided quiet (0.662) and unaided noise (0.617) whereas there was no significant correlation observed for the aided noise condition.

Finally, when the left ear was considered, it was again observed that there was no significant correlation between the behavioral scores and the frequency of F0 in any of the conditions. Also, it was observed that there was no significant correlation between the amplitude of F0 and the behavioral scores for all the conditions except for the unaided quiet condition, which showed a high correlation of 0.793.

Table 3.5

Correlation values between the behavioral scores and F0 amplitude across different conditions.

Independent Variable			**Correlation value**
Ear	Hearing aid	Condition	
Binaural	Aided	Quiet	0.781**
		Noise	0.613*
	Unaided	Quiet	0.679*
		Noise	0.614*
Right	Aided	Quiet	0.640*
		Noise	-
	Unaided	Quiet	0.662*
		Noise	0.617*
Left	Aided	Quiet	-
		Noise	-
	Unaided	Quiet	0.793**
		Noise	

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

In the asymmetric group, again the binaural condition was considered first. As observed in the symmetric group, there was no significant correlation between the behavioral scores and the frequency of F0 in any of the conditions. However, for the amplitude of F0, unlike the symmetric group, there was significant correlation observed only for aided quiet condition (0.709) and no significant correlations for the aided noise, unaided quiet and unaided noise conditions. When the right ear scores were taken into consideration, it was observed that there was no significant correlation for any of the conditions for both frequency of F0 and amplitude of F0. Similarly for the left ear scores, there were no conditions where there was significant correlation observed between the behavioral speech perception scores and the electrophysiological measures of F0 frequency and F0 amplitude.

As mentioned before, in order to understand the differences between the monaural and binaural conditions, the right and left ear scores were averaged to obtain a single monaural score for each of the conditions. This score was then further compared with the monaural and binaural data obtained for the electrophysiological analyses. Hence, here the correlations of binaural scores of behavioral speech perception with binaural electrophysiological data were observed as well as the correlation of the averaged monaural scores of the behavioral data with the electrophysiological data were observed.

In the symmetric group, for the binaural condition, it was observed that there was no significant correlation between the behavioral scores and the electrophysiological F0 frequency for any of the conditions. However, there was significant correlation between the behavioral and electrophysiological F0 amplitude for the aided quiet (0.790), aided noise (0.613), unaided quiet (0.679) as well as the unaided noise (0.614) conditions. For the monaural conditions, it was observed that there was no significant correlation when the behavioral data were compared with the frequency of F0. However; it was observed that there was a significant correlation between the behavioral data and the amplitude of F0 for aided quiet, aided noise (0.708), unaided quiet (0.728) as well as the unaided noise (0.757).

Table 3.6

Correlation values of different independent variables across the different conditions – comparison of binaural versus monaural.

Independent Variable			Correlation value
Ear	Hearing aid	Condition	
Binaural	Aided	Quiet	0.790**
		Noise	0.613*
	Unaided	Quiet	0.679*
		Noise	0.614*
Monaural	Aided	Quiet	0.712*
		Noise	0.708*
	Unaided	Quiet	0.728*
		Noise	0.757**

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Within the asymmetric group, for the binaural conditions, there was no significant correlation observed between the frequency of F0 and the behavioral data. Also, it was observed that there was no significant correlation between the F0 amplitude and the behavioral data for all the conditions except aided quiet (0.709). For the monaural conditions, similar to the binaural conditions, it was observed that there was no correlation between the F0 frequency and the behavioral scores. Also, there was no significant correlation between the behavioral scores and the F0 amplitude for any of the conditions.

In summary, it was observed that there was no correlation between the frequency of F0 and the behavioral speech perception scores, for all the conditions. The amplitude of F0 correlated significantly with behavioral scores within the symmetric group whereas within the asymmetric group, the behavioral scores correlated with the F0 amplitude only in a few conditions.

There is very little research which has correlated the speech perception scores to the electrophysiological representation of F0. Khaladkar, Karthik and Vanaja (2005) evaluated the relationship between behavioral speech perception and ABR measure and cortical AEPs in individuals with SNHL. Results revealed a significant relationship between SIS and speech evoked ABR. They concluded that cochlear hearing loss significantly impaired the representation of the burst and the transition portions of the speech evoked ABR. In the present study too, there was significant agreement between the speech perception and the amplitude of F0, but only for the symmetric hearing loss group and not for the asymmetric group.

The results can be explained based on the following assumptions. Individuals with symmetric hearing loss had good correlation with the behavioral scores because of the symmetry in hearing loss in both ears. Due to the symmetry, it can be assumed that the process of acclimatization to the hearing loss in the auditory structures might be easier and faster and possibly more accurate. However, in the asymmetric group, because of the asymmetry it might take greater time to get acclimatized to the hearing losses and the compensation might not be complete or accurate. Also the acclimatization process can be assumed to be at different speeds at the neurological level as well as for the behavioral perception. An extension of this is the acclimatization time required when individuals are fitted with binaural hearing aids, especially in case of asymmetric hearing loss. Rao and Manjula (2011) evaluated the role of plasticity and acclimatization in individuals with symmetric sensori-neural hearing loss using speech evoked ABR and late latency responses. They reported that over a period of 3 months used as acclimatization, there was significant improvement in the responses in the responses at both the brainstem and cortical level. Hence in the present study, it is possible that there might be lesser acclimatization for the asymmetric hearing loss group, as the whole procedure was completed during the process of hearing aid fitting and none of the subjects considered for the study were naïve hearing aid users.

Chapter 4

Summary and conclusions:

Cochlear hearing loss, being the most common type of hearing loss, is often associated with the damage to OHCs and/or IHC on the basilar membrane leading to many perceptual consequences such as increased (poorer) threshold of hearing, poorer speech perception (in quiet as well as in noise), loss of compressive non-linearity and greater masking effects. One of the greatest and the most frustrating difficulties faced by individuals with cochlear hearing loss is the inability to completely comprehend speech in the presence of background noise, an effect called as the “cocktail party effect”. Research has shown that this problem can be reduced by identifying specific segments of the target speech stimulus like the vocal quality, vocal fundamental frequency etc. This phenomenon is called “stream segregation”. However, there are numerous studies that have shown that individuals with SNHL have significantly poorer perception of F0, and hence the perception of vocal pitch can be thought to be affected. This can be further extended into supposing that a poorer perception of F0 is one of the major reasons why individuals with SNHL have such great difficulty in understanding speech in the presence of noise. The poorer perception of F0 in individuals with SNHL can also be related to the lack of synchronous neural representation of stimulus at the higher auditory structures – a critical requirement for satisfactory representation of speech representation on the auditory system.

As there are evidences of neural insufficiencies in terms of synchronous encoding of sound in cochlear hearing loss, it becomes necessary to understand the neurophysiologic processes underlying the process of encoding F0 in the auditory system. Many studies have clearly showed that the frequency following response can be successfully used to understand the F0 encoding capabilities of the auditory system, up till the level of the auditory brainstem.

Another significant contributor to the perception of speech in noise is the symmetry (or the lack of it) between the two ears. It is not yet conclusively understood if asymmetric hearing loss affects binaural hearing, and by extension binaural amplification. Hence the present study aimed at understanding the representation of speech (F0) at the auditory brainstem in individuals with symmetric and asymmetric hearing loss. The study also aimed at evaluating and comparing the representation of speech in different conditions such as aided versus unaided as well as quiet versus noise, in both the groups. Also, another main objective of the study was to observe the performance of both the groups when aided monaurally as well as binaurally. All the above conditions were kept constant for both behavioral as well as electrophysiological measurements.

A total of 29 subjects, in the age range of 35 - 55 years, were divided into symmetric (14 participants) and asymmetric groups (15 participants) with the criteria for asymmetric being greater than 10 dB HL but lesser than 25 dB difference in at least two frequencies across the two ears. Behavioral and electrophysiological measures were recorded for all subjects in three major conditions

- Monaural (predominantly right and predominantly left) versus binaural
- Aided versus unaided
- Quiet versus noise

For the behavioral testing 20 different nonsense VCV combinations of the different consonants of Kannada language in the vowel environment of /a/ were used, whereas for the electrophysiological testing, the same vowel /a/ was used (synthesized with F0 = 100Hz). Statistical analysis for the behavioral data showed no significant difference between the symmetric and asymmetric groups in all the conditions considered, although there was a trend for the symmetric group to be better. The same results were obtained even when the binaural was compared to the mean of the monaural (M_R & M_L). However, within the groups it was observed that the binaural conditions had better scores than both the monaural (M_R &M_L), aided scores were better than the unaided as well as the scores in quiet conditions were higher than in noise conditions.

For the electrophysiological testing, there was no significant difference between the symmetric and asymmetric hearing loss for any of the conditions when the frequency of the F0 (after FFT analysis) was considered. Even when the amplitude of F0 was considered, there was no statistically significant difference between the two groups. However, within the groups it was observed that, quite similar to the behavioral data, the binaural conditions were better than monaural conditions, aided conditions were better than the unaided conditions and quiet conditions were better than the noise conditions. Even when the binaural performance was compared to the mean of the monaural (M_R &M_L), similar results were obtained.

The similarity of responses across the two groups in all the conditions can be attributed to the ability of the auditory brainstem to overcome inter-aural asymmetries, even in the presence of asymmetric hearing loss. Also it was assumed that the hearing loss at 4000 Hz, which in the present study were always less than 60 dB HL, were not sufficient enough to cause any significant distortions to the waveforms of the FFR across both the groups to yield a statistically significant difference.

The enhanced encoding of the F0 in quiet conditions in comparison with the noise conditions were attributed to the reduction in the synchronicity of the firing of neurons when background noise is introduced, leading to less robust representation of F0 relative to the response in quiet. The enhancement of the F0 representation in the aided conditions was assumed to be because of the auditory system being sensitive to enhanced or amplified sounds. Based on other electrophysiological test like LLRs and click-ABRs, it was deduced that the enhancement seen in the amplitudes of these obligatory responses can also be extended to the encoding of F0 at the auditory brainstem, when measured using the speech evoked ABRs.

When the behavioral and electrophysiological results were tested for correlations, it was observed that there was no correlation between the frequency of F0 and the behavioral scores. However, there were significant correlations for various conditions when the F0 amplitude was tested for correlations with the behavioral scores. The correlations were observed to be higher and present in more number of conditions (out of the 12 conditions totally considered) for the symmetric group than the asymmetric group. The relatively lesser or poorer correlation of the asymmetric group in comparison with the symmetric group was assumed to be because of the asymmetry and the lack of time available for acclimatizing oneself with a hearing aid, both for behavioral and electrophysiological testing.

Overall the conclusions drawn from the present study are

- there was no statistical difference between the symmetric and asymmetric groups for any of the conditions,
- symmetric hearing loss resulted in slightly better speech perception than asymmetric hearing loss, for all conditions,
- aided conditions were better than unaided conditions
- quiet conditions led to better speech perception than noise conditions

Future directions

- The results of the present study indicated that there was no significant difference between the symmetric and asymmetric hearing loss populations. However, considering that the numbers of subjects in both the groups were fairly limited, it is warranted that a future study with greater number of subjects in both the groups will be able to yield more noteworthy results.

- The present study, being a preliminary one, used the hearing aid parameters at their most basic settings to avoid any time delays that may be introduced had any of the special features like noise reduction, directionality etc. were kept on. Future studies might be taken up to investigate the effects of all these special features on the electrophysiological representation of speech in the brainstem and beyond.
- Invasive studies, although not completely under the purview of an audiologist, might be carried out to understand the effects of cochlear hearing loss on individual nerve fibers to better understand the neural pathophysiology associated with different types and causes of cochlear hearing loss. Knowing the pathophysiology might enable the audiologist to formulate better strategies to more efficiently rehabilitate individuals with SNHL.
- Although it is reported that musicians have shown enhanced auditory and perceptual behaviors, there are no systematic studies reported in literature that have used behavioral as well as electrophysiological measures to understand if musicians with hearing loss have any superiority over non musicians with hearing loss. To understand this further, research needs to be focused on how musical training can offset the deleterious effects of hearing loss.

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