RELATION BETWEEN CONSONANT PERCEPTION AND PSYCHOACOUSTIC MEASURES IN INDIVIDUALS WITH AUDITORY DYS-SYNCHRONY

Register No: 09AUD018

A Dissertation Submitted in Part Fulfilment of Final Year

Master of Science (Audiology)

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June – 2011

Certificate

This is to certify that this dissertation titled ***"Relation between consonant perception and psychoacoustic measures in individuals with auditory dys-synchrony"*** is a bonafide work of the student with Registration No: 09AUD018 submitted in part fulfilment for the degree of Master of Science (Audiology). This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any diploma or degree.

Mysore
June, 2011

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Certificate

This is to certify that this dissertation titled ***"Relation between consonant perception and psychoacoustic measures in individuals with auditory dys-synchrony"*** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.

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DECLARATION

This is to certify that this dissertation titled ***"Relation between consonant perception and psychoacoustic measures in individuals with auditory dys-synchrony"*** is the result of my own study under the guidance of **Dr. Animesh Barman,** Reader in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other university for the award of any diploma or degree.

Mysore **Register No. 09AUD018**

June, 2011

Dedicated to,

Amma, Naana

and

My guide

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Chapter 1

Introduction

Festive season is the best time to feast our eyes with colours and variegated patterns of shapes/words/messages created by serial lights. The serial lights have to be managed in great sync so as to create the desired shapes. An even slight disturbance in the sync among the different bulbs would cause a visual aberration and the desired shape/configuration would be disturbed. This implies that timing is a very important feature for the perception of the shapes and configurations in a serial light formation.

The visual aberration caused by the timing disturbance in a serial light formation is analogous to the auditory aberration caused by timing disturbance in the auditory nerve fibres in individuals with Auditory Neuropathy/Dys-synchrony (AN/AD). The term auditory dys-synchrony was coined by Starr, Picton, Sininger, Hood & Berlin, (1996). Auditory dys-synchrony is a hearing disorder characterized by normal cochlear amplifier and disordered afferent neural transmission (Zeng, Kong, Michalewski, & Starr, 2005; Starr et al. 1996).

Berlin, Hood, Morlet, Wilensky, St. John, Montgomery and Thibodaux. (2005), Hood, Berlin, Bordelon and Rose. (2003) and Starr et al. (1996) have reported the following audiological findings in individuals with AN/AD:

- Hearing sensitivity ranging from normal hearing sensitivity to profound hearing loss.

- Speech identification scores disproportionate to the degree and configuration of hearing loss especially, very poor speech identification scores in the presence of noise.
- Elevated or absent middle ear reflexes, disproportionate to the degree and type of hearing loss.
- Absent auditory brainstem responses. If present, the waveforms have very poor morphology.
- Present or robust oto-acoustic emissions (TEOAE & DPOAE).
- Present cochlear microphonics, often of a long ringing type.
- Absent or very less contralateral suppression of TEOAE and DPOAE.

The most striking feature that defines auditory dys-synchrony is the absence of the action potentials in spite of normal oto-acoustic emissions. It is not clear as yet if the pathology in AN/AD lies at the level of the synapse of the inner hair cell and auditory nerve, the auditory nerve itself or at the level of the inner hair cell.

The disrupted action potentials in AN/AD have been attributed to three different possibilities by Rance (2004). Those are Myelin disorder, axonal neuropathy or inner hair cell loss. These cause a loss of synchrony in the neural discharges or abnormal/reduced neural discharges which prevent the summation of the single nerve discharges to combine and be recorded from a far field site as the auditory brainstem responses. A more serious consequence of this asynchronous firing of the neural discharge is disruption in the timing information to be transmitted, analogous to the serial lights example.

It has been shown by Drullman et al. (1994) and Zeng et al. (1999) that temporal smearing of speech signals disrupts the perception of speech by reducing the energy contrast between the consonant and vowel and it also affects the spectral contrast making it more difficult to extract the salient cues for consonant and vowel recognition. Zeng et al. (1999) showed that there was a good correlation between the speech identification abilities and the temporal modulation transfer function in AN/AD. Also, they found that simulations of affected temporal processing resulted in similar speech perception results as seen in AN/AD. And so was the conclusion of various other studies (Rance, McKay & Grayden, 2004; Zeng et al., 2005; Zeng et al., 1999). Kumar and Jayaram, (2005) reported that the impaired speech perception abilities in individuals with AN/AD is predominantly due to the temporal processing deficit. They also saw a very poor correlation between the pure-tone thresholds and speech perception abilities and said that audibility is not a factor in the impairment in speech perception in AN/AD.

The greater edge in speech perception impairment in AN/AD has always been given to the impaired temporal processing deficits, however there are other deficits in speech sound processing which have not been well explored in conjunction with the speech perception abilities in AN/AD. One of them is the frequency resolution.

The frequency resolution has been studied in AN/AD by Vinay and Moore (2007). They reported that their subjects with AN/AD had lower Q_{10dB} values compared to the Q_{10dB} values obtained by Kluk and Moore (2005) in individuals with normal hearing loss and reported that the Q_{10dB} values are lower in individuals with AN/AD. Barman (2008), Zeng et al. (2005) have shown that individuals with AN/AD have greater difference limens for frequency compared to normal hearing individuals, this too throws light on the impaired frequency resolution abilities in individuals with auditory dys-synchrony.

The impaired frequency resolution has been identified as the main reason for speech perception deficits in cochlear hearing loss with greater than moderate degree of hearing loss (Thornton & Abbas, 1980; Sterlcyk & Dau, 2009; Glasberg & Moore, 1989). They have also shown that the temporal envelope processing is slightly impaired at low sensation levels and not at high sensation levels. The results of these studies might also imply that the impairment in the frequency selectivity might also be a significant factor in the impairment of speech perception in individuals with auditory dys-synchrony. Hence, the deficits in temporal processing and frequency selectivity might interact to cause impairment in speech perception abilities in AN/AD.

1.2 Need for the study

Most of the studies on speech perception in individuals with auditory dys-synchrony have concentrated on correlating the percentage of speech identification scores with the psychoacoustic test results. However, the scores as such do not give information on what phonetic features a person is able to or not able to perceive, and it does not give a correct picture about the speech perception abilities in individuals with auditory dys-synchrony. There are only a handful of studies (Narne & Vanaja, 2008; Rance et al. 2010) assessing the perception per se based on the phonetic features perceived in auditory dys-synchrony.

Narne and Vanaja (2008) analysed consonant confusion matrices using information transfer analysis in auditory dys-synchrony. They found that VOT errors predominated followed by place errors and then the manner errors. However, psychoacoustic tests were not performed which could have helped to explain if the perception errors seen were because of a temporal or a spectral processing deficit.

Rance et al. (2010) analysed the open-set consonant perception in auditory dys-synchrony along with temporal modulation transfer function (TMTF) for modulation frequencies of 10, 50 and 150 Hz. Individuals with auditory dys-synchrony had difficulty following slow and fast temporal fluctuations, but the modulation frequencies used by them are not conventionally used, and the modulation frequencies below 10Hz are the ones which significantly contribute to speech perception. Further, they also analysed the open set consonant perception results using information transfer analysis. But open set consonant identification task frequently gives rise to an irregular matrix and information transfer analysis results cannot be relied upon when performed on an irregular matrix (Wang & Bilger, 1973). To tap the ability to perceive the temporal envelope cues in speech it is necessary that the amplitude modulation detection ability be studied at more modulation frequencies within the range of 2 Hz to 50 Hz, as the temporal envelope of speech ranges from 2 Hz to 50 Hz (Rosen, 1992). Additionally data on modulation detection abilities in AN/AD suggests a relatively greater decrease in the modulation detection thresholds at frequencies lower than 10 Hz and greater than 64 Hz (Zeng et al., 2005, Kumar & Jayaram,2006). Typical speech contains periodicity information in the range of 50 Hz to 500 Hz which suggests that individuals with AN/AD have difficulty processing the periodicity information too. These data suggest that, to analyse the temporal resolution in relation with speech perception in individuals with AN/AD, it is important to study the temporal resolution at more modulation frequencies between the range of 2 Hz to 50 Hz and also modulation frequencies above 50 Hz.

In addition to the above, there are only a handful of studies which have assessed the frequency resolution in auditory dys-synchrony. Vinay and Moore (2007) investigated frequency resolution using psychoacoustic tuning curves (PTCs) using a simultaneous narrow-band noise masking. But the simultaneous narrowband noise masking technique has its disadvantages i.e. the occurrence of beats and off-frequency listening. Glasberg and Moore (1986) have suggested the use of notched noise maskers to rule out the effects of beats and off-frequency listening. This suggests that further studies are needed to assess frequency resolution in individuals with AN/AD.

There are no controlled studies that have assessed temporal and frequency resolution and their relation to consonant perception in auditory dys-synchrony. Hence, there is a need to study the temporal resolution, frequency resolution and consonant perception in the following manner:

- ✓ Closed set consonant identification with information transfer function analysis.
- ✓ Temporal resolution with more modulation frequencies to have a detailed picture about the temporal resolution abilities.
- ✓ Frequency resolution abilities using a notched noise masking method to eliminate off-frequency listening and to avoid the occurrence of beats (Glasberg & Moore, 2000).
- ✓ The relative contribution of each of the deficits (temporal resolution and frequency resolution) to impaired speech processing.
- ✓ The comparison of the role of frequency resolution and temporal resolution deficits in impaired speech perception abilities in individuals with auditory dys-synchrony.

Studying the relation between temporal and frequency resolution and speech perception abilities in cochlear hearing loss population would help us to know how the frequency resolution deficits affect the consonant perception in the absence of significant temporal deficits (Rance, McKay & Grayden, 2004; Zeng, Kong, Michalewski & Starr: 2005). This would help in delineating the errors occurring due to a frequency resolution deficit alone.

1.3 Objectives of the present study

Thus, the current study was taken up with the following objectives:

- To study the Consonant Perception in individuals with auditory dys-synchrony.
- To study the frequency resolution ability in individuals with auditory dys-synchrony.
- To study the temporal resolution ability in individuals with auditory dys-synchrony.
- To observe the pattern of errors seen in consonant perception and their relation with temporal and frequency resolution in individuals with auditory dys-synchrony.
- To investigate similarities and differences in the consonant perception, temporal resolution and frequency resolution abilities in auditory dys-synchrony and cochlear hearing loss.

Chapter 2

Review of Literature

Auditory neuropathy/Dys-synchrony is a form of hearing impairment in which cochlear outer hair cell function is spared but neural transmission in the auditory pathway is disordered (Starr *et al.*, 1996; Berlin *et al.*, 2001). The degree of hearing loss in AN/AD ranges from minimal to profound hearing loss. Normal hearing sensitivity in AN/AD is also very commonly seen. The cardinal feature of AN/AD is the disproportionate speech identification scores relative to the degree of hearing loss (Berlin et al., 2005; Hood et al., 2003; Starr et al., 1996)

2.1 Prevalence of Auditory Neuropathy/Dys-synchrony

The reported prevalence rate varies from 0.11%, to 0.5% (Davis & Hirsh, 1979; Kraus, Ozdamar, Stein & Reed 1984; Rance, et al., 1999; Tang, Mcpherson, Yuen, Wong, & Lee, 2004). Tang et al. reported a prevalence rate of 2.44% in school-aged hearing impaired children. Rance et al. (1999) reported a prevalence rate of 0.23% in 5199 babies with risk factors for hearing loss. Kumar & Jayaram (2006) reported a prevalence rate of 0.54% in individuals with sensory neural hearing loss. They also reported the male to female ratio of 2:1.

2.2 The pathophysiology of Auditory Neuropathy/ Dys-synchrony

Starr et al. (2003) conducted a histopathological study of the cochlea and auditory nerve in an individual with AN/AD. They found that the organ of corti was normal throughout the cochlea except in the apical turn which had a 30% loss of outer hair cells. The inner hair cells were normal throughout the cochlea. They found a profound loss of spiral ganglion cells (95% loss). The remaining auditory nerve fibers had thin myelin sheaths. Starr et al. (1991) also said that the pathology in AN/AD can also be at the level of the synapse between inner hair cell and the auditory nerve's terminal receptor sites. This might be caused due to an affected neurotransmitter release mechanism or the neurotransmitter receptor mechanism. Varga et al. (2003) reported disruption of the Otoferlin protein in individuals with AN/AD, disruption of which affects the neurotransmitter release. McMahon et al., (2009) explained two mechanisms in AN/AD (i) pre-synaptic mechanism and (ii) post-synaptic mechanism. One group with post-synaptic neuropathy had summating potential at a normal latency followed by a dendritic potential and no action potentials, however they had normal morphology electrically evoked auditory brainstem response (eABR) testing. Another group had summating potentials at prolonged latency and no dendritic potentials were seen, however they had normal morphology eABRs. This points to the fact that there is a subgroup of AN/AD which has deficits in the cochlear mechanism and the inner hair cells.

Currently, it is very difficult to pinpoint the exact site of lesion in AN/AD. This is because of the wide variety of causes leading to AN/AD and the wide variety of manifestations in the pathos-physiological observations evidenced in literature.

2.3 Degree and configuration of Hearing loss

Starr, Sininger and Pratt. (2000) in their 67 patients with AN/AD found that 31% had average hearing levels less than 35 dB HL, 39% had average hearing levels between 35 and 70 dB HL and 30% had average hearing levels greater than 75 dB HL. Among the 67 subjects they tested, 41% had audiograms with low frequency emphasis (rising/reverse slope pattern), 29% had an irregular saw-tooth pattern, 5%

had an ‘U’ shaped audiogram, 5% showed a tent shaped loss with peak at 2 kHz, and the remaining 11% had a high frequency sloping hearing loss.

Zeng et al. (1999) reported a range of 7 to 62 dB HL average hearing levels in individuals with AN/AD. They also reported that most of their AN/AD subjects had a low frequency hearing loss.

Kumar and Jayaram (2005) in their 14 subjects with AN/AD found that 5 subjects had a rising audiometric pattern, 8 subjects had a peaked audiometric pattern and 1 subject had flat audiometric pattern. The average hearing levels in their subjects ranged from 5 dB HL to 75 dB HL.

Kumar and Jayaram (2006) reported audiometric findings in 61 subjects with AN/AD. Out of the 61 subjects, 26 subjects had a peaked audiogram, 11 had a rising audiogram, 8 had a saucer shaped (middle frequencies 20 dB better than the low and high frequencies) and 3 showed a high frequency sloping audiogram, the rest 2 subjects were babies whose pure tone thresholds could not be established. They reported that, among the subjects with peaked audiograms, 77% showed a peak in the audiogram at 2000 Hz. The degree of hearing loss in them ranged from mild to severe and there was no significant difference in the degree of hearing loss across ears.

2.4 Psychoacoustical measures in individuals with Auditory Neuropathy/dys-synchrony

Numerous studies have been done in individuals with AN/AD assessing the psycho-acoustical abilities in AN/AD. The following is a brief overview of the psycho-acoustic findings in AN/AD:

- ✓ Marked deficits in temporal resolution on tests of Gap detection and Temporal modulation detection (Barman, 2008 ; Zeng et al.,2005 ; Kumar & Jayaram., 2005)
- ✓ Deficits in frequency discrimination on tests of Difference limen for Frequency (Barman, 2008 ; Zeng et al., 2005)
- ✓ Relatively spared difference limens for intensity (Barman, 2008 ; Zeng et al., 2005)
- ✓ Excessive masking on a simultaneous masking task (Zeng et al., 2005)

The deficits on Gap detection and Temporal Modulation detection, point towards affected temporal processing in the auditory system. Relatively spared intensity difference limens indicate spared intensity processing. Excessive masking on simultaneous masking task and the poor difference limens for frequency, point towards either disrupted frequency selectivity or impaired temporal resolution in the auditory system. The speech perception deficits in AN/AD in literature, have been attributed mainly to the temporal processing deficits with relatively spared intensity and frequency processing.

2.4.1 Temporal Processing and speech processing deficits AN/AD

Temporal processing deficit is the main processing deficit in individuals with AN/AD. Barman (2008), Kraus et al.(2000), Rance et al. (2004) and Zeng et al. (2005), have shown that individuals with AN/AD have poor temporal processing as evidenced by the poor gap detection scores.

Temporal modulation transfer function (TMTF) is a function depicting modulation thresholds based on the modulation frequencies. The TMTF can be derived by assessing the threshold for detection of sinusoidal amplitude modulations in a pure tone or a noise carrier at different modulation frequencies. The TMTF gives information about the auditory systems ability to follow the temporal changes in an on-going signal. Speech too is an amplitude modulated signal with the amplitude fluctuations ranging from 2 Hz to 50 Hz, hence a complete TMTF is very well representative of perception of amplitude fluctuations in speech. The TMTF is low pass in shape in normal hearing individuals (Eddins, 1993).

Zeng et al. (2005), have shown that individuals with AN/AD had reduced sensitivity to the amplitude modulations in an on-going signal. The AN/AD subjects had a lower peak sensitivity of –8.7 dB (37% modulation) and a lower cut-off frequency of 17.0 Hz (r =0.81). Whereas, the normal controls in their study showed a typical low-pass pattern, with peak sensitivity of –19.9 dB (10% modulation) and 3-dB cut-off frequency of 258.1 Hz (r = 0.96). They concluded that the temporal modulation transfer function (TMTF) has a band-pass characteristic in individuals with AN/AD as a result they are less sensitive to slow and fast temporal changes in an on-going signal.

Zeng et al. (1999) studied temporal modulation transfer functions (TMTF) in AN/AD, cochlear hearing loss, and normal listeners. They found that normal listening group and cochlear hearing loss group had similar bandwidth (232 Hz) and peak sensitivity (-20.4 dB) on the TMTF. Whereas, the AN/AD group had reduced bandwidth (47 Hz) and peak sensitivity (-10.2 dB). This implies that the temporal processing deficit is the cardinal feature of AN/AD as compared to cochlear hearing loss. They also found that the TMTFs had a good correlation with the speech processing deficits in AN/AD. However the speech feature errors and their correlation with temporal processing deficit were not analysed in this study.

Rance et al. (2008) studied TMTF and gap detection thresholds in conjunction with speech perception in AN/AD and cochlear hearing loss group. They found that there was a significant correlation between the temporal processing deficits and the phoneme identification based on the timing cues (the VOT & Vowel duration cues) in the AN/AD group. They found that the voicing errors were more prominent followed by place errors and the manner errors. However, there was no correlation between the temporal processing abilities and the phoneme perception in the cochlear hearing loss group.

Rance et al. (2004), assessed amplitude modulation detection thresholds and perception of consonant-nucleus-consonant nonsense syllables in individuals with AN/AD. The AN/AD group was divided into two sub-groups based on their speech perception scores. The sub-group with higher speech perception scores (>30%) demonstrated higher peak sensitivity (-14.3 dB) compared to the subgroup with lower speech perception scores (<30%) who showed an average peak sensitivity of (-4.4 dB). Statistical analysis showed a good correlation ($r^2 = 0.77$) between modulation detection and speech perception scores.

There is a consistent agreement across studies that the temporal modulation transfer function correlates well with the speech perception abilities. There is also a general agreement across studies that the speech features which are perceived based on the temporal cues are the ones which are the most affected in AN/AD i.e. the voicing cues (voice onset time & vowel duration cues) and the manner cues.

2.4.2 Frequency resolution and speech perception deficits in AN/AD

Frequency resolution/selectivity is the ability of the human ear to resolve two closely placed frequency components. It is this ability of frequency resolution which dictates the frequency discrimination.

Frequency resolution has not been studied in detail in the AN/AD population. There are studies on AN/AD which have studied frequency resolution indirectly by studying the frequency discrimination. There are only a handful of studies which have used psychoacoustic tuning curves and a few other techniques to assess frequency resolution.

Zeng et al. (2001) studied frequency discrimination in individuals with AN/AD. They found that difference limen for frequency (DLF) of 8 kHz was similar to that of normal hearing subjects. For frequencies below 8 kHz the DLFs were markedly poorer than the normal hearing subjects. These poor low frequency DLFs in the presence of near normal 8 kHz DLF has been attributed to the temporal processing of the low frequency signals in AN/AD.

Rance et al. (2004) studied the frequency discrimination in AN/AD. The mean DLF for 4 kHz was 4.5 times that of the normal hearing subjects. The DLFs for 500 Hz were 11 times poorer in the AN/AD subjects when compared to the normal hearing subjects. They concluded that individuals with AN/AD were less able to use phase-locking cues as compared to normal hearing individuals and individuals with cochlear hearing loss with the same degree of hearing loss. Additionally, they found a strong relationship between frequency discrimination and open-set speech identification, their subjects with the poorest frequency discrimination had the poorest speech perception scores.

Zeng et al., (2005) studied the frequency discrimination in AN/AD for frequencies ranging from 250 Hz to 8000 Hz. They found that for frequencies less than 1000 Hz, individuals with AN/AD had DLFs which were twice that of their normal hearing controls. They also found that the difference between the groups reduced with frequency, and the difference in the DLF at 8 kHz was not statistically significant between the two groups. Thus they concluded that the frequency discrimination at lower frequencies which is mediated by the temporal mechanisms is significantly impaired in AN/AD, however frequency discrimination at 8 kHz which is predominantly perceived through place mechanisms is spared.

However, the results of frequency discrimination in the above studies do not indicate at the frequency resolution abilities in AN/AD. Moore (1973) and Sek and Moore (1995) reported that the frequency discrimination of frequencies above 4 kHz is primarily dependent on the information provided by the place mechanisms, whereas, the frequency discrimination for the lower frequencies is dependent on the temporal cues. Moore (1973), Patterson and Moore (1986) found no significant relationship between frequency discrimination abilities and frequency resolution abilities in individuals with cochlear hearing loss. They attributed this to the fact that frequency discrimination task assesses the perception of pitch which is dependent on the perception of the temporal cues whereas, frequency resolution measures how well can sounds of different frequencies be resolved on the basilar membrane.

Cacace, Satyamurti and Grimes (1983) measured the psychoacoustic tuning curves in Friedrich’s Ataxia with AN/AD. They found that the Psychoacoustic tuning curves (PTC) from 500 Hz to 2 kHz were sharply tuned in these individuals. However this cannot be generalized to the rest of the AN/AD population as the pathology in this population is more so at the brainstem level.

Kraus et al (2000) assessed the frequency resolution at 1 kHz. They measured tonal thresholds in the presence of a 1 kHz bandpass noise with bandwidth of 800 Hz and also in the presence of the same noise with a spectral notch (notchwidth = 500 Hz). They obtained a threshold of 79 dB SPL in the no notch condition and a threshold of 72 dB SPL in the notched noise condition. They concluded that, individuals with AN/AD have reduced abilities to separate remote spectral components.

Vinay and Moore (2007) measured the psychoacoustic tuning curves in AN/AD. They found that there was no shift in the tip of the PTC from the probe frequency. They also calculated the Q_{10dB} values and reported that the Q_{10dB} values were lower than that of the normal hearing listeners in the study by Kluk and Moore (2004). This is suggestive of widened auditory filters in AN/AD. A few of the AN/AD subjects also showed multiple tips and erratic patterns, which might be a consequence of the occurrence of beats and off-frequency listening due to the use narrow-band noise. However, the authors explain that the lower Q_{10dB} values might be because of higher intensity levels used for testing; this cannot be confirmed as no controls were taken up for the study, and the lower Q_{10dB} values could be very well a consequence of compromised frequency resolution. Additionally, the PTC data shown by them is not consistent with the observation of Zeng et al. (2004) that there is over-masking in individuals with AN/AD. This over-masking should have caused an overall rise in the tip of the PTC, which is not evident from the PTC data of Vinay and Moore (2007). This might imply that there could have been an artifactual interference in the measurement of PTC in the AN/AD subject using a simultaneous narrow-band noise masking technique.

The above two studies indicate at a deficit in frequency resolution in individuals with AN/AD. And it has been well established in literature by Thibodeau and van Tasell (1987) and Moore and Ohgushi (1993) that frequency resolution using a notched noise technique showed a good correlation with consonant perception in individuals with cochlear hearing loss. As frequency resolution is very important in resolving the spectral components in speech, especially in perceiving consonant spectrum and the formant transitions in speech and also in the perception speech sounds with very fine spectral difference (Moore, 1995). Moore (1995) further says that these broad auditory filters in cochlear hearing causes an increased susceptibility to upward spread of masking, which would lead to the low frequency vowel energy masking out the higher frequency consonant energy. This affected frequency resolution might also be an important factor deciding speech perception in individuals with AN/AD.

Rance, Mckay and Grayden (2004) assessed the frequency resolution in children with AN/AD. They studied the level of two different maskers needed to mask a 1 kHz pure tone at a level of 70 dB SPL. The maskers considered in this study were a white noise masker with a notch in the spectrum from 750 Hz to 1250 Hz and an unmodified white noise masker. They considered the difference in the masker level required to mask the 1 kHz pure tone across the two masker conditions as a measure of frequency resolution. They found that this measure of frequency resolution was not significantly different across their normal and AN/AD group whereas there was significant difference between the normal and SN groups. They concluded that frequency resolution was not a factor in determining the open-set speech perception ability in individuals with AN/AD. The frequency resolution measure in this study was limited to one frequency (1 kHz) which is not representative of the frequency resolution of the whole cochlea. Also the results of this study are in contrast to the results of Kraus et al. (2000) who showed very little change in the signal threshold in a notch and no notch masking condition. The differences in the results of the two studies might also be a consequence of the difference in the methods used i.e. Kraus et al. (2000) used a noise with bandwidth of 500 Hz and a spectral notchwidth of 800 Hz whereas, Rance, Mckay and Grayden (2004) used a white noise masker with a spectral notch width of 500 Hz, also the former used a fixed masker level condition and the latter used a fixed probe level condition, the latter further used a low level pink noise in the subjects in the normal hearing group to simulate the effects of elevated threshold.

Frequency resolution has not been studied in depth in literature. The use of more precise methods to study frequency resolution using notched noise masking technique at more frequencies representative of the frequency selectivity of the cochlea important for speech perception is warranted. The relation between frequency resolution and speech perception has not been studied in detail in the AN/AD population. Studying this relation would provide more insight into the auditory processing in individuals with AN/AD.

Chapter 3

Method

The method of this study included the analysis of the pattern of errors seen in consonant perception in individuals with auditory dys-synchrony. Frequency resolution and temporal resolution measures were obtained to know their relationship with consonant perception measures.

3.1 Participants

A total of 30 participants were included in the study. They were divided into two clinical groups and one control group. All the participants were literate with mother tongue being Kannada and they could read the Kannada script without any difficulty.

3.1.1 *Clinical Group 1: Auditory Dys-synchrony group*

Eleven participants clinically diagnosed as having auditory dys-synchrony were included in Clinical Group I (AN/AD group). Participants with pure-tone thresholds ranging from normal to moderate degree were taken up for the study and those with greater degrees of hearing loss were not included in the study. The age-range of the participants was 13 – 34 years with a mean age of 24.4 years.

The criteria for diagnosis of Auditory Dys-synchrony were:

- ✓ Pure-tone thresholds ranging from 0 dB HL to 45 dB HL, and air-bone gap within 10 dB HL.
- ✓ Absent or very poor Auditory Brainstem Responses.
- ✓ Normal Transient Evoked Oto-acoustic emissions.

- ✓ Abnormal or absent acoustic reflexes with no indication of middle ear pathology on tympanometry.
- ✓ Disproportionately poor speech identification scores with respect to the audiometric thresholds or abnormal speech identification scores in the presence of noise in those with good speech identification in quiet.

The details of the participants with AN/AD are shown in table 3.1. Out of the 18 ears in this study, 11 ears had normal hearing thresholds, 3 ears had mild hearing loss with peak at 2 kHz and 4 ears had mild hearing loss with a flat audiometric pattern.

Table 3.1

The Audiometric details of the participants with AN/AD

Participant	Age	Hearing sensitivity	SIS	Audiometric pattern
AN1	27	Normal	70	Flat
AN2	27	Normal	70	Flat
AN3	19	Normal	64	Flat
AN4	19	Normal	68	Flat
AN6	34	Normal	44	Flat
AN5	34	Normal	40	Flat
AN7	18	Normal	20	Flat
AN8	18	Normal	16	Flat
AN9	21	Normal	80	Flat
AN10	21	Normal	80	Flat
AN11	13	Mild	36	Flat
AN12	13	Mild	36	Peaked
AN13	31	Mild	40	Peaked
AN14	31	Mild	36	Peaked
AN15	31	Mild	32	Flat
AN16	31	Mild	36	Flat
AN17	35	Mild	24	Flat
AN18	17	Mild	12	Flat

3.1.2 *Clinical Group 2: Cochlear hearing loss group*

Seven ears, i.e. four participants clinically diagnosed as having cochlear hearing loss were taken up for the study. The participants taken up in this group had severity of hearing loss and audiometric configuration matched to the participants with auditory dys-synchrony who had hearing loss. 3 of the ears with cochlear loss had mild hearing loss with peak at 2 kHz and the other 4 had mild flat cochlear hearing loss. The sub-group with mild hearing loss and peak at 2 kHz was called 'CochHL-Peak' and the sub-group with mild flat hearing loss was called 'CochHL-Flat'. The age range of the participants in this group was 19 – 35 years with a mean age of 25 years.

The criteria for diagnosing cochlear hearing loss were:

- ✓ Elevated Air-conduction and Bone-conduction thresholds with Air Bone Gap within 10 dB HL.
- ✓ Acoustic reflexes proportional to the degree of hearing loss with no indication of middle ear pathology.
- ✓ 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.
- ✓ Speech identification scores proportionate to the degree of hearing loss for cochlear pathology.
- ✓ No history of neurological or otological symptoms.

3.1.3 *Control Group:*

Ten participants with an age range of 18 – 26 with a mean age of 21 years were considered for the study. The control group was called the ‘Normal’ group in this study. The following criteria were considered for the selection of participants in this group:

- ✓ Pure tone thresholds within 15 dB HL through frequencies 250 Hz to 8000 Hz.
- ✓ Speech Identification scores greater than 60% at 0 dB SNR for PB word list.
- ✓ A or As type Tympanogram with Acoustic reflex thresholds within 95 dB HL.
- ✓ Presence of Transient Evoked Oto-acoustic emissions.
- ✓ No history of neurological or otological symptoms.

3.2 Instrumentation

- ✓ A PC with Matlab version 7, Adobe Audition 1.5 software was used for conducting the experiments.
- ✓ Psychoacoustics Toolbox developed by Grassi and Soranzo (2007) for Matlab was used for assessing the frequency resolution using a notched noise masking method and for the temporal modulation detection test.
- ✓ APEX 3 program developed at ExpORL (Francart, van Wieringen, & Wouters, 2008) was used to regulate the presentation of stimuli and recording of responses for consonant perception.
- ✓ A set of programs called Feature Info Ixfer (FIX) developed by the department of phonetics and linguistics in University College London was used to perform Sequential Information Transfer Function Analysis (as described by Wang & Bilger, 1973).

- ✓ A Tucker Davis Technology System-3 equipped with RP2.1 processor, a PA5 programmable attenuator and a HB7 headphone buffer were used to control the level of the stimuli for assessment of consonant perception, frequency resolution and temporal resolution.
- ✓ Madsen OB-922, a two channel diagnostic audiometer was used for estimating the pure-tone thresholds and for doing speech audiometry.
- ✓ A Grason – Stadler Inc. Tympstar instrument was used to perform tympanometry and reflexometry.
- ✓ ILO – V6 instrument was used to assess outer hair cell functioning by measuring the Transient Evoked Oto-acoustic Emissions.
- ✓ Intelligent Hearing systems Evoked potential instrument with Opti-amp was used to record the Auditory Brainstem Responses.

3.3 Procedure

3.3.1 *Audiological evaluation in the subject selection procedure*

The following are the details of the test used in the selection procedure:

Pure-Tone Audiometry

Air conduction and bone conduction pure-tone thresholds were measured using a calibrated clinical audiometer Madsen OB-922. Pure-tone audiometry was carried out using modified version of Hughson and Westlake procedure.

Immittance Evaluation

Tympanometry and reflexometry was done using a calibrated GSI-Tympstar immittance meter. Tympanograms were obtained for 226 Hz probe tone. Ipsilateral and contralateral acoustic reflex thresholds were measured at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

Speech Audiometry

Phonemically Balanced word list in Kannada developed by Yathiraj and Vijayalakshmi (2005) was used to assess open set speech perception abilities using live voice in these subjects. Half lists of 25 bisyllabic meaningful words of Kannada were used for testing. The Speech identification testing was done at the most comfortable level of the participants.

Transient evoked Oto-acoustic Emission Evaluation

TEOAEs were obtained using click stimuli at a presentation level of 80+/- 5 dB pkSPL. The clicks were presented in a non-linear mode for 260 sweeps of four clicks each. And a criterion of 3 dB SNR with reproducibility greater than 80% was used as the criteria for considering TEOAE to be present.

Auditory Brainstem Response evaluation

The following protocol was used for assessing the Auditory Brainstem Response as shown in Table 3.2. The auditory brainstem responses (ABR) were recorded using an IHS Opti-amp evoked potential instrument equipped with SmartEP 3.94 USBeZ software. The ABR testing was done to evaluate the eighth nerve functioning. The ABR was recorded at a low stimulation rate (11.1/sec) and a high stimulation rate (90.1/sec) to assess the eighth nerve functioning.

Table 3.2

The protocol used for the acquisition of auditory brainstem responses.

Acquisition Parameters		**Stimulus Parameters**	
Montage	A1 – Cz– A2	Transducer	ER – 3A insert ear phones (300 Ω)
Sweeps	1500	Stimulus	Click (100 µsec)
Filter	100 – 3000 Hz	Polarity	Rarefaction and condensation
Analysis epoch	0 – 15 msec	Intensity	90 dB nHL
Artifact rejection	31 µV	Stimulation rate	11.1 clicks/sec and 90.1/sec
Notch Filter	on		

3.3.2 Procedure used to obtain the data

It consisted of the following experiments:

Experiment I – Assessment of temporal resolution

Experiment II – Assessment of the frequency resolution

Experiment III – Assessment of consonant Perception

Experiment I – Assessment of Temporal Resolution

This experiment involved the estimation of the threshold for the detection of sinusoidal amplitude modulation of a carrier signal across different modulation frequencies. The details of the experiment are as follows:

Stimuli

Broadband noise was used as a carrier on which sinusoidal modulations were imposed to test for the amplitude modulation detection abilities. The Noise carrier denoted as n(t) with a total duration of 500 msec and 20 msec raised-cosine onsets and offsets were generated, where 't' = 500 msec is the duration of the noise signal. Sine waves of frequencies equal to 4, 8, 16, 32, 64, 128, 256 Hz were generated based on the Equation 3.1. These sine waves were the modulators used to modulate the broadband noise carriers.

$$\text{Modulator} = a\text{Sin}\,(2\pi ft) \qquad \text{.. Equation 3.1}$$

Where f is the desired modulation frequency with an amplitude 'a' and duration 't' of the sine wave. Each sine wave was then DC shifted and multiplied to the broad band noise to obtain the modulated noise of desired modulation frequencies. The equation for the generation of the modulated noise is as shown in equation 3.2.

$$\text{Modulated noise} = c[1 + m \sin(2\pi f_m t + \phi_m)] \times n(t) \ \{\text{as in Viemeister 1979}\}$$

.. Equation 3.2

'm' is the modulation depth ($0 \leq m \leq 1$), 'f_m' is the modulation frequency (f_m was 2, 4, 8, 16, 32, 64, 128, 256 and 512 Hz), and 'ϕ_m' is the starting phase of the modulation, randomized on each interval. The term 'c' is a multiplicative compensation term (Viemeister, 1979) set such that the overall power will remain the same in all intervals. The expression for 'c' is given by equation 3.3

$$c = [1 + m^2/2]^{-0.5}$$

... .Equation 3.3

Procedure

Modulation detection threshold was obtained using a 3 Interval - 3 Alternative Forced Choice procedure at modulation frequencies of 4, 8, 16, 32, 64, 128, 256Hz at 60 dB SPL. The modulation depth was varied from 0 to -40 dB {modulation depth = 20log(m) } using 2Down and 1Up stepping rule to converge upon the 70.7% point on the psychometric function. The starting step size was 8 dB and after the first reversal the step size was reduced to 2 dB. A total of six reversals were considered, and the average of the last five reversals was considered as the modulation detection threshold.

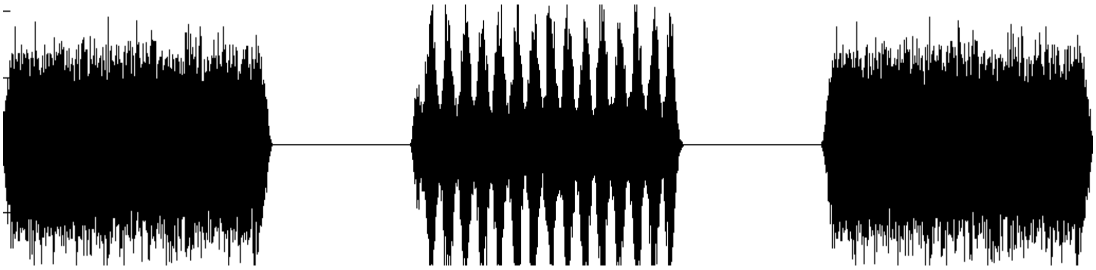

Figure 3.1. The unmodulated and modulated noise signals in a single trial

Response Pattern

The participants were made to indicate verbally or by pressing the keys on the keyboard as to which of the three tokens had a modulated noise or which of the three tokens sounded different from the other two. If in any trial the participants found all the three tokens to be the same, then they were asked to make a random guess and answer.

Experiment II – Assessment of the frequency resolution

This experiment involved the assessment of thresholds for the detection of a pure tone in the presence of notched noise maskers. The details of the experiment are as follows:

Stimuli

Pure tones of frequencies (Fc) 500 Hz, 1000 Hz and 2000 Hz with durations of 300 msec were used as the test stimuli and were generated using equation 3.4. Notched noises centered at frequencies (Fc) 500 Hz, 1000 Hz and 2000 Hz were used as the masking stimuli.

$$\text{Pure tone} = a\text{Sin}(2\pi ft) \qquad \text{…Equation 3.4}$$

Broad band noise of 400 msec was generated with flat amplitude across all frequencies. The noise was then modified in the FFT domain. To create the notch, the noise was altered in the spectral domain by setting all the frequency components lying between $Fc \pm (g \times Fc)$ **(**'Fc' is the probe signal frequency and 'g' is the normalized notchwidth $\frac{|f-Fc|}{Fc}$**,** where *f* is the edge frequency of the notch on either side of Fc**)**. The outer edges of the noise bands were restricted to $0.8 \times Fc$ on either side of the probe frequency, by setting the amplitude of frequencies beyond $Fc \pm 0.8 \times Fc$ to zero amplitude to create bands of noises on either side of the notch.

The intensity of the notched noise was set to 50 dB SPL across all the noise components. This was done by first normalizing the amplitude of noise across all frequency components so that the amplitude at all the frequency components is equal to 1. Then the amplitude of a 50 dB SPL sinusoidal tone of 1000Hz in the FFT domain is taken as a reference and this was multiplied to the notched noise to obtain a constant amplitude across all frequency components in the noise which is equal to the amplitude of the 50 dB SPL tone of 1 kHz.

Finally the time domain notched noise with intensity of 50 dB SPL/Hz was obtained by the inverse FFT. The filtering process leads to an increase in the noise duration due to ringing of the filter. From this filtered noise, a time slice of 400 msec was used in the experiment for the purpose of masking the probe tone.

Notched noises centered at 500 Hz, 1000 Hz and 2000 Hz were generated using the above mentioned method. The normalized notchwidths used were, g equal to 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5

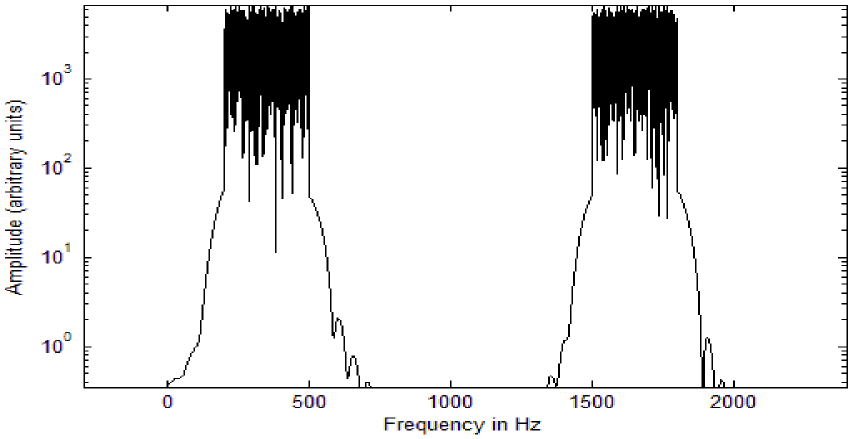

Figure 3.2. Spectrum of notched noise with Fc= 1000 Hz and g = 0.5

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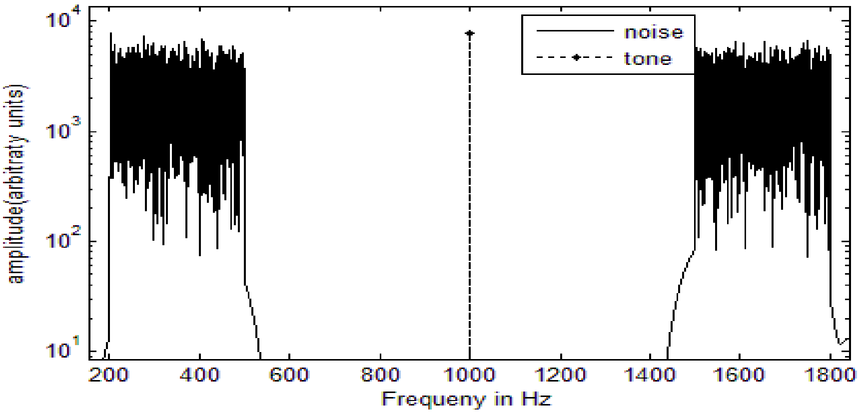

Figure 3.3. Spectrum of notched noise centered at 1000 Hz with g = 0.5 along with the 1000 Hz probe tone

The Noise and the Probe signals were gated using a cosine ramp of rise/fall time of 20 msec. The notched noises were then mixed with the probe signals to constitute the variable signal with the pure tone placed at the temporal center of the masking stimuli. A 400 msec notched noise alone token constituted the standard signal

Procedure

The notched noise was presented at 50 dB SPL/Hz. The thresholds for the probe signals as a function of notch width was tested in a 3 Interval - 3 Alternative Forced Choice procedure using a psychoacoustic toolbox in Matlab developed by Grassi and Soranzo (2007).

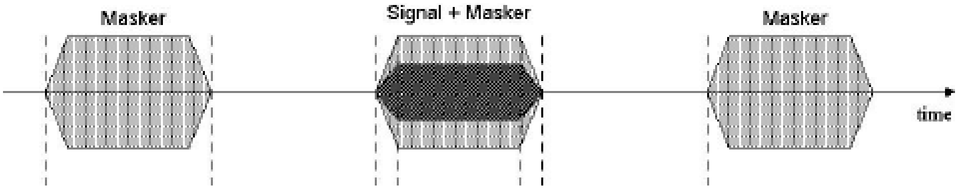

Figure 3.4. Time domain representation of the stimulus token presented in one trial

The level of the probe signal was varied using a 2Down-1Up stepping rule to converge on to the 70.7% point on the psychometric function at each notch width for each probe frequency. The starting step size was 8 dB and after the first reversal the step size was reduced to 5 dB and the following reversals had a step size of 2 dB. A total of eight reversals were considered, and the average of the last six reversals was considered as the threshold for the detection of the tone in the presence of the notched noise.

Response Pattern

The participants were made to indicate verbally or by pressing the keys on the keyboard as to which of the three tokens presented had a tone in them. If the participant did not hear any tone (s)he was asked to respond with a random guess. The Matlab code for conducting this experiment has been given in Appendix I.

Experiment III - Assessment of consonant Perception

This experiment involved the assessment of closed consonant identification using a software interface. The details of the experiment are as follows:

Stimuli

Twenty consonants | p t k b d g t^h d^h ʧ ʤ l r m n h j ṇ w ḷ s ʃ | were chosen to study the perception of all the consonants in kannada by those with Auditory dys-synchrony. These consonants were chosen as they are the most commonly occurring consonants in the kannada language. The speech tokens were recorded in the voices of three adult male native speakers of Kannada language. The consonants were recorded in the context of a vowel |a| in the initial and final position in a clearly articulated manner to create 20 non-meaningful vowel-consonant-vowel (VCV) combinations (e.g. |ata| |aga)|. The recording was done using Adobe Audition version 1.5 software at a sampling frequency of 44100 Hz and resolution of 16 bits. As each speaker recorded a list of 20 VCV tokens, this resulted in a list of sixty tokens (20 tokens × 3 speakers) of multi-talker consonants. The speech tokens were recorded by three different speakers so as to obtain consonant recognition score as recommended by Kraus (2000). The multi-talker condition was chosen as this is representative of the real-life situation because in a real-life situation we have to be listening to speech produced by different talkers.

Procedure

The consonant perception testing was performed using APEX 3 software. Apex 3 presents the speech tokens in a randomized order. The speech tokens are presented monaurally by the APEX 3 software. After the presentation of each stimuli participant had to respond by pressing the appropriate button, the software controls the presentation of the stimulus and the next stimulus was presented 200 msec after the participants response. All the speech stimuli were presented monaurally at the most comfortable levels for the participants.

Response pattern

Twenty VCV combinations were displayed on a computer screen in Kannada script using a graphical user interface on an APEX 3 platform. The participants were made to respond to the speech stimuli by clicking on the appropriate VCV combination out of the twenty VCV combinations displayed on the computer screen. Figure 3.5 shows the response interface of the consonant identification test used on the APEX 3 platform.

Figure 3.5. The response interface for the consonant perception test

In all the experiments the stimuli from the sound card of the PC were reproduced by the RP2.1 processor (TDT sys3) at 50 kHz sampling rate and attenuated using a PA5 programmable attenuator to achieve desired intensity levels. The PA5 output was then used to drive a pair of Sennheisser HDA200 headphones through an HB7 headphone buffer.

3.3.4 Analyses

The AN/AD group were divided into three subgroups based on the degree and pattern of hearing loss. The first group consisted of 11 individuals with normal hearing sensitivity (AN/AD normal), the second consisted of 3 individuals with mild low frequency hearing loss with peak at 2 kHz (AN/AD-Peak) and the third group consisted of 4 individuals with mild flat hearing loss (AN/AD-Flat). The controls consisted of 18 normal hearing individuals (normal), 3 individuals with low frequency cochlear hearing loss and peak at 2 kHz (CochHL-Peak) and 4 individuals with mild flat cochlear hearing loss (CochHL-Flat). All the comparisons were made both across groups and across sub-groups.

Temporal Resolution

Temporal modulation transfer function (TMTF) was obtained from the temporal modulation detection data by fitting the data to a lowpass butterworth filter as in Zeng et al.(2004).

$$y = -20\log(xo/(1+(f/fc)^{2n}) \qquad \text{…Equation 3.5}$$

Where y is modulation index (m) in dB { -20log(m)}, f is the modulation frequency in hertz, –20log(xo) is the peak sensitivity or gain in dB, and fc is the approximate 3-dB cut-off frequency or bandwidth in hertz and n is the order of the filter. The parameters peak sensitivity of the TMTF denoted by ‘Pk’ and bandwidth of the TMTF denoted by ‘BW’ were derived from the above fitting function. Where Pk is equal to -20log(xo) and BW is equal to Fc. These two parameters ‘Pk’ and ‘BW’ were the measures of temporal resolution and were used for further analysis

Frequency resolution

Auditory filter shapes were derived by fitting the notched noise data to a double rounded exponential function as used by Moore and Glasberg (1990). The curve fitting is done using ‘roexpr’ program developed by Glasberg and Moore (1992) on an RM/Fortran platform. The roex parameters ‘p’, ‘r’ and ‘ERB’ are derived from the curve fitting using the equation 3.4.

$$Wg = (1 - r) \times (1 + p \times g) \times \exp(-p \times g) + r \qquad \text{… Equation 3.4}$$

Where, Wg is the auditory filter and the parameter ‘p’ denotes the slope of the peak of the filter (pass band), the parameter ‘r’ denotes the slope of the tail of the filter and the parameter ERB denotes the equivalent rectangular bandwidth of the derived auditory filters. The equivalent rectangular bandwidth (ERB) is calculated by the equation 3.5. Where, ‘p’ is the slope of the pass band of the auditory filter, ‘r’ is the slope of the tail of the auditory filter, ‘a’ is a constant and Fc is the center frequency of the auditory filter .

$$\text{ERB} = (4\text{Fc}/ p) \times (a \times r) \qquad \text{…Equation 3.5}$$

The p, r and ERB parameters for 500 Hz are denoted as p500, r500 and ERB500. The p, r and ERB parameters for 1000 Hz are denoted as p1000, r1000 and ERB1000. The p,r and ERB parameters for 2000 Hz are denoted as p2000, r2000 and ERB 2000.

Consonant Perception

Consonant confusion matrices were drawn based on the responses to the VCV combinations. The confusion matrices were then subjected to Sequential Information Transfer Function Analysis (SINFA) using FIX to analyze the pattern of errors. The matrices were analyzed according to parameters of manner, place and voicing features. The feature matrix used for SINFA analysis is shown in Figure 3.1. The conditional information is calculated as number of bits of information transmitted per each feature out of the total number of bits of information held by the available per feature, this was called conditional information. Appendix II shows the sample feature matrix used for SINFA analysis and appendix III shows a sample consonant confusion matrix.

The deficits in the frequency resolution and temporal resolution were compared across the groups. The correlation between the parameters of frequency resolution and temporal resolution with that of the information transmitted for manner, place and voicing feature was evaluated. The parameters which yielded the best correlation were then used to fit a model through linear regression to investigate the relationship between each speech feature and the temporal resolution and frequency resolution in AN/AD.

Chapter 4

Results

The study focussed on the comparison of temporal resolution, frequency resolution and consonant perception abilities in individuals with Auditory neuropathy/dys-synchrony (AN/AD) with that of individuals with cochlear hearing loss and normal hearing individuals. The temporal resolution, frequency resolution and consonant perception parameters each, were first compared across the groups and then compared across sub-groups. The correlations between the temporal and frequency resolution parameters with that of the consonant perception parameters were then analysed. Finally, regression analysis was done to arrive at models to explain the effect of temporal and frequency resolution on the consonant perception. All the statistical analyses in this study were performed using SPSS v18 software package. The Figures and plots were drawn using Systat 13 and Matlab v7 softwares.

4.1 Temporal resolution

The arithmetic means and standard deviations of the modulation detection thresholds across the AN/AD group, cochlear hearing loss group and the normal hearing group are displayed in Table 4.1. The mean modulation detection thresholds of each group have been displayed for the modulation frequencies of 2 Hz, 4 Hz, 8 Hz, 16 Hz, 32 Hz, 64 Hz, 32 Hz, 64 Hz 128 Hz, 256 Hz and 512 Hz. Figure 4.1 shows the temporal modulation transfer function (TMTF) for the three groups i.e modulation detection thresholds plotted across the modulation frequencies.

Table 4.1

Means and standard deviations for the modulation detection threshold (modulation depth) expressed in dB across the modulation frequencies in the three groups.

Groups	**Mean & S.D**	**Modulation detection threshold across modulation frequencies in dB**								
		2 Hz	**4 Hz**	**8 Hz**	**16 Hz**	**32 Hz**	**64 Hz**	**128 Hz**	**256 Hz**	**512 Hz**
AN/AD	**Mean**	-3.5	-7.7	-8.6	-9.4	-7.0	-4.1	-2.0	-0.1	0.0
	S.D	2.9	3.8	5.1	5.4	3.9	4.2	2.7	0.3	0.0
CochHL	**Mean**	-10.4	-14.7	-16.3	-18.3	-17.3	-14.1	-7.4	-2.6	0.0
	S.D	7.4	5.4	3.9	1.3	3.8	1.9	3.6	2.7	0.0
Normal	**Mean**	-18.3	-19.2	-21.2	-21.0	-20.3	-18.2	-16.5	-12.5	-9.9
	S.D	1.2	1.6	2.0	2.1	1.8	1.2	2.1	1.7	1.2

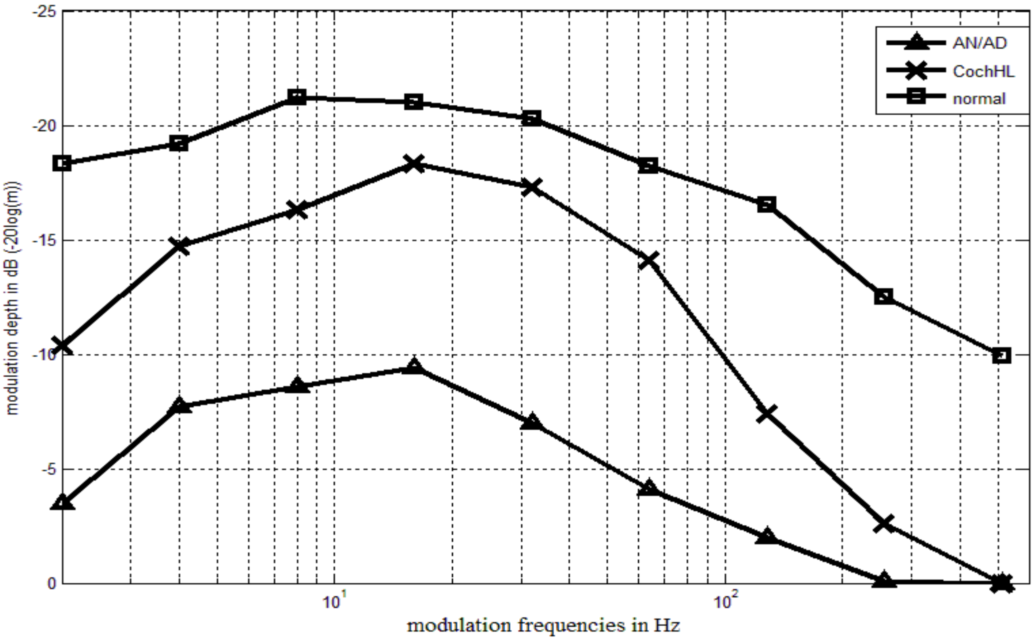

Figure 4.1. The modulation detection threshold (modulation depth) obtained in normal, cochlear and AN/AD groups, plotted across the modulation frequencies (logarithmic x-axis).

By visual inspection of Table 4.1 and Figure 4.1, it is evident that the mean modulation detection thresholds (modulus of the mean thresholds) for the AN/AD groups are lower than normal and are lower at the low and high modulation frequencies compared to the other modulation frequencies. The AN/AD group was subdivided into three subgroups based on the degree and pattern of hearing loss. The first group consisted of 11 individuals with normal hearing sensitivity (AN/AD-Normal), the second group consisted of 3 individuals with mild low frequency hearing loss with peak at 2 kHz (AN/AD-Peak) and the third group consisted of 4 individuals with mild flat hearing loss (AN/AD-Flat). The controls consisted of 18 normal hearing individuals (normal), 3 individuals with low frequency cochlear hearing loss and peak at 2 kHz (CochHL-Peak) and 4 individuals with mild flat cochlear hearing loss (CochHL-Flat). The arithmetic means and standard deviations of the subgroups are shown in Table 4.2, and have been plotted as mean TMTFs across the different sub-groups.

Table 4.2

Means and standard deviations for the modulation detection thresholds in dB (modulation depth) across modulation frequencies in the subgroups of AN/AD and CochHL groups.

Groups	Mean & S.D	Modulation detection thresholds across modulation frequencies								
		2 Hz	**4 Hz**	**8 Hz**	**16 Hz**	**32 Hz**	**64 Hz**	**128 Hz**	**256 Hz**	**512 Hz**
AN/AD Normal	**Mean**	-4.2	-7.8	-8.0	-9.3	-7.5	-5.5	-2.8	-.1	0
	S.D	3.3	4.8	6.0	5.3	3.7	3.5	3.0	.3	0
AN/AD Peak	**Mean**	-3.6	-8.0	-10.8	-13.6	-9.3	-4.0	-1.3	-.3	0
	S.D	.58	2.0	1.8	.5	3.2	6.9	2.3	.6	0
AN/AD Flat	**Mean**	-1.50	-7.0	-8.5	-6.5	-3.5	-.5	0	0	0
	S.D	1.9	.8	3.7	6.2	2.8	.5	0	0	0
CochHL Peak	**Mean**	-4.00	-13.0	-13.0	-18.0	-20.3	-12.3	-4.3	0	0
	S.D	.00	6.9	1.7	1.7	.5	1.1	2.8	0	0
CochHL Flat	**Mean**	-15.1	-16.0	-18.7	-18.5	-14.9	-15.5	-9.7	-4.5	0
	S.D	6.1	4.6	3.1	1.0	3.4	.5	2.0	1.7	0

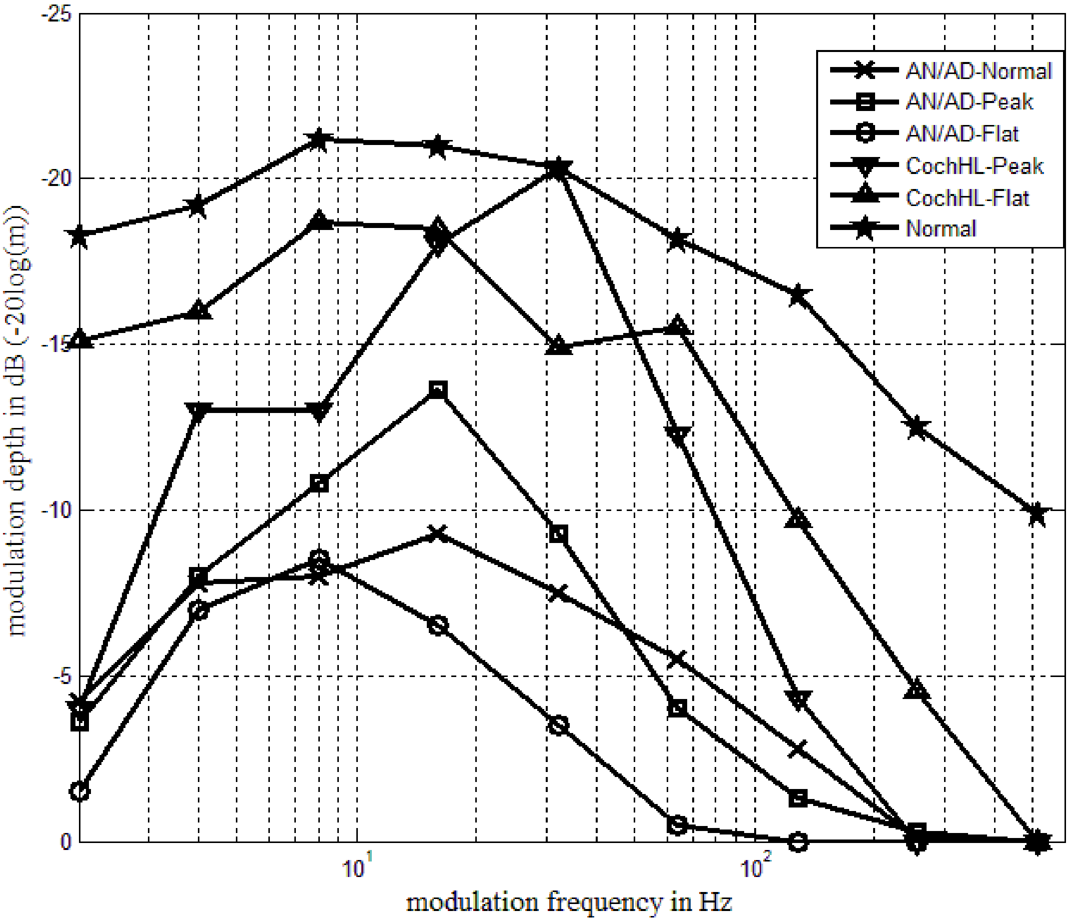

Figure 4.2. TMTF across the three subgroups of AN/AD and CochHL groups.

Visual inspection of Table 4.2 and Figure 4.2 showed that the CochHL-Flat sub-group had lower mean modulation thresholds (modulus of the modulation thresholds) than the CochHL-subgroup for the low modulation frequencies but were similar for the higher modulation frequencies. The AN/AD-Normal and AN/AD-Peak sub-groups had mean modulation thresholds greater than the AN/AD-Flat sub-group. The AN/AD-Peak subgroup had slightly higher mean modulation thresholds for the mid-modulation frequencies compared to the AN/AD-Normal sub-group. The AN/AD-Peak and AN/AD-Normal sub-groups had higher mean modulation thresholds compared to the AN/AD-Flat sub-group for the higher modulation frequencies. The AN/AD sub-groups as well as the CochHL- subgroups had a steeper drop in the modulation thresholds for the higher modulation frequencies compared to the normal TMTF. The same was also seen for the frequencies below 8 Hz for the CochHL-Flat and the AN/AD sub-groups, whereas, the CochHL-Peak subgroup did not have this steep drop in the thresholds at the low modulation frequencies.

From the TMTF data obtained, peak sensitivity (Pk) and bandwidth (BW) were derived to quantify the TMTF for each individual. This was done by fitting the modulation thresholds of each individual to a low-pass butterworth filter as described in section 3.3.4. The means and standard deviations for Pk and BW for the three groups and also the different sub-groups are shown in Table 4.3.

It can be seen from Table 4.3 that the mean Pk and BW are lower in the AN/AD group and its subgroups compared to the sub-groups of CochHL group and the Normal group. It can also be seen that Pk was similar between the CochHL group and the Normal group. However, BW is lower in the CochHL group compared to the Normal group.

The AN/AD group had lower Pk (in the text Pk is referred to as the modulus of Pk) and BW compared to the normal and the CochHL group. The standard deviation of BW however, is quite high in the AN/AD group compared to the other groups considering the low mean Pk. The Pk across the subgroups of AN/AD were similar with slightly higher Pk for the AN/AD-Peak sub-group. The BW was the most reduced in the AN/AD-Flat sub-group compared to the other AN/AD sub-groups.

The CochHL sub-groups had greater BW and Pk compared to the matched AN/AD sub-groups. The Pk was similar to that of the Normal group, however the BW was lower.

Table 4.3

Means and standard deviations of peak sensitivity in dB and Bandwidth in Hz across the groups and sub-groups.

Groups	Mean & S.D	Pk in dB	BW in Hz	Sub-groups	Mean & S.D	Pk in dB	BW in Hz
AN/AD	**Mean**	-10.78	23.00	**Normal**	**Mean**	-10.02	24.89
					S.D	4.50	18.36
				Peak	**Mean**	-13.67	23.88
	S.D	3.96	16.42		**S.D**	0.58	15.26
				Flat	**Mean**	-10.75	17.18
					S.D	3.30	13.80
CochHL	**Mean**	-20.25	54.91	**Peak**	**Mean**	-20.33	53.67
					S.D	0.58	17.67
	S.D	0.44	12.62	**Flat**	**Mean**	-20.20	55.85
					S.D	0.40	10.38
Normal	**Mean**	-21.72	72.70				
	S.D	1.80	5.26				

Kruskal-Wallis test done to compare ‘Pk’ and ‘BW’ across the groups ignoring the pattern of hearing loss revealed significant difference across the three groups. The results of Kruskal-Wallis test across groups are shown in Table 4.4.

Table 4.4

Results of the Kruskal –Wallis test comparing the AN/AD group, CochHL group and the Normal group.

Temporal resolution	χ^2	**df**	**Asymp. Sig.**
Pk	32.012	2	.000
BW	31.623	2	.000

Mann-Whitney U test was administered to see the significant difference across groups. The results showed that AN/AD group differed significantly from the Normal and the CochHL groups for both the parameters Pk and BW. The CochHL group differed significantly from the Normal group in terms of BW but did not differ significantly from the Normal group in terms of Pk.

Table 4.5

Pairwise comparison of ‘Pk’ across the three groups using Mann- Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant $p < 0.01$	
Normal	Significant $p < 0.01$	Not Significant $p > 0.05$

Table 4.6

Pairwise comparison of 'BW' across the three groups using Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant $p < 0.01$	
Normal	Significant $p < 0.01$	Significant $p < 0.05$

The Pk and BW were compared across all the subgroups of AN/AD and CochHL groups using non-parametric Kruskal-Wallis test and the results are shown in Table 4.7. Kruskal-Wallis test revealed a significant difference among the subgroups for both Pk and BW across the sub-groups. Mann-Whitney U test was then performed within the subgroups to know which of the subgroups are different.

Table 4.7

Results of Kruskal-Wallis test comparing the Pk and BW across all the sub- groups.

Temporal resolution	χ^2	**df**	**Asymp. Sig.**
Pk	32.537	5	.000
BW	31.844	5	.000

Table 4.8 shows the pairwise comparison for Pk across the sub-groups. There was no significant difference in Pk among the sub-groups of AN/AD or within the CochHL groups. Pk in all the AN/AD sub-groups was significantly different from the CochHL sub-groups and the Normal group. The Pk in CochHL sub-groups however, did not differ significantly from the Normal group.

Table 4.8

Pairwise comparison of subgroups for peak sensitivity using Mann-Whitney U test.

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
CochHL	Peak	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Not Significant $p > 0.05$	Not Significant $p > 0.05$

Table 4.9 shows the pairwise comparison for BW across the the subgroups AN/AD and CochHL. There was no significant difference among the sub-groups of AN/AD and CochHL groups for BW. BW in all the AN/AD sub-groups differed significantly from the CochHL subgroups and the Normal group. Pk in the CochHL-Peak sub-group did not vary significantly from that of the Normal group however, the Pk in CochHL-Flat sub-group was significantly different from the Normal group.

Table 4.9

Pairwise comparison of subgroups for the parameter BW (bandwidth) using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
Cochlear	Peak	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Not Significant $p > 0.05$	Significant $p < 0.05$

4.2 Frequency resolution across the groups

The arithmetic means and standard deviations of the frequency resolution parameters (roex parameters) ‘p’, ‘r’ and ‘ERB’ across the three groups are shown in Table 4.9. p500, p1000 and p2000 represent the slope of the peak of the auditory filters at frequencies 500 Hz, 1000 Hz and 2000 Hz respectively. r500, r1000 and r2000 represent the slope of the tail of the auditory filters at frequencies 500 Hz, 1000 Hz and 2000 Hz respectively. ERB500, ERB1000 and ERB2000 represent the equivalent rectangular bandwidth of the auditory filter for frequencies 500 Hz, 1000 Hz and 2000 Hz respectively. Table 4.10 and Table 4.11 show the mean and standard deviations for the roex parameters across the groups and subgroups respectively.

Table 4.10

Means and standard deviations across the groups for the roex parameters 'p', 'r' and 'ERB' for frequencies 500 Hz, 1000 Hz and 2000 Hz.

Groups	**Mean and S.D**	**p**			**r**			**ERB**		
		p500	**p1000**	**p2000**	**r500**	**r1000**	**r2000**	**ERB500**	**ERB1000**	**ERB2000**
AN/AD	**Mean**	32.04	12.10	13.41	-16.31	-38.47	-49.13	500.77	492.46	746.82
	S.D	19.70	6.11	6.10	28.12	35.46	38.70	311.98	220.67	316.30
CochHL	**Mean**	12.89	13.70	15.00	-48.33	-24.07	-66.16	164.07	318.29	653.37
	S.D	2.47	3.08	6.56	44.85	9.50	44.34	24.95	76.01	316.43
Normal	**Mean**	16.59	16.13	13.99	-56.57	-54.18	-48.95	124.15	158.56	426.59
	S.D	6.47	5.60	4.11	37.24	30.84	39.20	24.19	25.29	75.10

Table 4.11

Means and standard deviations across the sub-groups for the roex parameters (‘p’, ‘r’ and ‘ERB’) for the frequencies 500 Hz, 1000 Hz, 2000 Hz.

Sub-groups	**Mean and S.D**	**p**			**r**			**ERB**		
		p500	**p1000**	**p2000**	**r500**	**r1000**	**r2000**	**ERB500**	**ERB1000**	**ERB2000**
AN/AD Normal	**Mean**	31.87	13.20	15.55	-21.20	-43.98	-52.84	554.05	449.93	605.85
	S.D	20.68	6.46	6.87	35.41	40.33	38.99	327.07	143.58	127.37
AN/AD Peak	**Mean**	34.40	10.20	11.43	-12.83	-36.13	-75.93	271.07	550.83	730.73
	S.D	21.95	3.86	2.79	5.39	42.25	42.28	80.30	154.56	191.33
AN/AD Flat	**Mean**	30.75	10.50	9.00	-5.45	-25.05	-18.85	526.55	565.65	1146.55
	S.D	21.07	7.13	1.11	5.13	12.51	15.38	355.82	417.26	449.73
CochHL Peak	**Mean**	13.87	14.57	19.13	-55.53	-31.03	-66.43	151.63	277.23	431.90
	S.D	3.67	.75	2.20	50.48	3.47	66.45	33.16	14.73	49.44
CochHL Flat	**Mean**	12.15	13.05	11.90	-42.93	-18.85	-65.95	173.40	349.08	819.48
	S.D	1.24	4.16	7.27	47.26	9.36	31.43	15.52	91.98	335.84
Normal	**Mean**	16.59	16.13	13.99	-56.57	-54.18	-48.95	124.15	158.56	426.59
	S.D	6.47	5.6	4.11	37.24	30.84	39.2	24.19	25.29	75.1

Kruskal-Wallis test was performed across the three groups to compare the roex parameters ignoring the pattern of hearing loss. The results of the Kruskal-Wallis test across the three groups are shown in Table 4.18. Kruskal-Wallis test showed significant difference between the groups for the parameters r500, and r2000, ERB1000 and ERB2000. However, the parameters p500, p1000, p2000, r2000 and ERB2000 were not significantly different across groups. The groups were then compared in a pairwise manner using Mann-Whitney U test to assess which groups were significantly different.

Table 4.12

Results of Kruskal-Wallis test comparing the roex parameters across the three groups.

roex parameters	**Frequency resolution**	**χ^2**	**df**	**Asymp. Sig.**
p	p500	4.237	2	.120
	p1000	5.831	2	.054
	p2000	1.233	2	.540
r	r500	22.159	2	.000
	r1000	9.818	2	.007
	r2000	1.573	2	.455
ERB	ERB500	32.629	2	.000
	ERB1000	32.598	2	.000
	ERB2000	18.638	2	.000

Table 4.12, 4.13, 4.14, 4.15, 4.16, and 4.17 show the results of Mann-Whitney U test pair wise comparison of r500, ERB500, r1000, ERB1000, ERB2000 across the groups. The three groups were significantly different for the parameters ERB500 and ERB1000. The parameter r 500 was significantly different between the Normal and AN/AD groups, but not between the CochHL and Normal groups. r1000 was

significantly different between the AN/AD group and the Normal group, however, it did not differ significantly between the CochHL and the AN/AD groups. There was a significant difference between the AN/AD group and the Normal group only for ERB2000.

Table 4.13

Pairwise comparison of r500 across groups using the Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant p < 0.01	
Normal	Significant p < 0.01	Not Significant p > 0.05

Table 4.14

Pairwise comparison of r1000 across groups using the Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Not Significant p > 0.05	
Normal	Significant p < 0.05	Significant p < 0.01

Table 4.15

Pairwise comparison of ERB500 across groups using the Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant $p < 0.01$	
Normal	Significant $p < 0.01$	Significant $p < 0.01$

Table 4.16

Pairwise comparison of ERB1000 across groups using the Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant $p < 0.05$	
Normal	Significant $p < 0.01$	Significant $p < 0.01$

Table 4.17

Pairwise comparison of ERB2000 across groups using the Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Not Significant $p >0.05$	
Normal	Significant $p < 0.01$	Not Significant $p > 0.05$

Kruskal-Wallis test was carried out to check for the differences across the subgroups of AN/AD and CochHL groups for the roex parameters (‘p’, ‘r’ and ‘ERB’) for frequencies 500 Hz, 1000 Hz and 2000 Hz. The test revealed significant differences for p2000, r500, r1000, ERB500, ERB1000, and ERB2000 across the subgroups. However p500, p1000 and r2000 did not show any significant differences across the subgroups.

Table 4.18

The results of Kruskal-Wallis test to check for the difference across the sub-groups of AN/AD and CochHL for roex parameters (*‘p’, ‘r’ and ‘ERB*).

roex parameters	Frequency resolution	χ^2	df	Asymp. Sig.
p	p500	4.441	5	.488
	p1000	7.733	5	.172
	p2000	14.564	5	.012
r	r5000	23.143	5	.000
	r1000	11.001	5	.051
	r2000	7.283	5	.200
ERB	ERB500	33.216	5	.000
	ERB1000	33.165	5	.000
	ERB2000	24.814	5	.000

Mann-Whitney U test was performed to check which of the subgroups were significantly different in terms of each roex parameter. r500 was significantly different between all the AN/AD sub-groups and the Normal group and between the AN/AD flat sub-group and the two CochHL subgroups, which can be seen in Table 4.19.

Table 4.19

Pairwise comparison of 'r500' across the sub-groups using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
Cochlear	Peak	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Significant $p < 0.05$		
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Not Significant $p > 0.05$	Not Significant $p > 0.05$

The pairwise comparison of r1000 across all the sub-groups is shown in Table 4.20. The Normal group was significantly different from both the AN/AD and CochHL having flat configuration only.

The pairwise comparison of all the sub-groups for ERB500 is shown in Table 4.21. AN/AD sub-groups differed significantly from the Normal group and all the sub-groups of CochHL. There was no significant difference between the CochHL-Peak sub-group and the Normal group.

Table 4.20

Pairwise comparison of 'r1000' across the sub-groups using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
Cochlear	Peak	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$		
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	
Normal	-	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	Significant $p < 0.01$

Table 4.21

Pairwise comparison of 'p2000' across the sub-groups using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Significant $p < 0.01$	Not Significant $p > 0.05$			
Cochlear	Peak	Not Significant $p > 0.05$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	
Normal	-	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Significant $p < 0.01$	Significant $p < 0.05$	Not Significant $p > 0.05$

The pairwise comparison for p2000 across the sub-groups is shown in Table 4.23. p2000 was significantly different between the AN/AD-Flat and the AN/AD-Normal sub-groups. The p2000 in the Normal group was significantly different from the AN/AD-Flat sub-group and the CochHL-Peak subgroup. Also, the p2000 in the CochHL-Peak sub-group was significantly different from the AN/AD-Peak and the AN/AD-Flat sub-group.

Table 4.22

Results of Pairwise comparison of 'ERB500' across the subgroups

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
Cochlear	Peak	Significant $p < 0.01$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Significant $p < 0.01$	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Not Significant $p > 0.05$	Significant $p < 0.01$

The Pairwise comparison for ERB1000 across the groups is shown in Table 4.22. ERB1000 in the Normal group was significantly different from all the sub-groups of AN/AD and CochHL. AN/AD-normal and AN/AD-peak sub-groups were significantly different from the CochHL-Peak sub-group only.

Table 4.22

Pairwise comparison of 'ERB1000' across the sub-groups using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
Cochlear	Peak	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$		
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$

The pairwise comparison of ERB2000 across the subgroups is shown in Table 4.24. ERB2000 was significantly different between all the sub-groups of AN/AD and the Normal group and the CochHL-Peak subgroup. Also, there was a significant difference between AN/AD-Normal sub-group and the AN/AD-Flat sub-group for ERB2000. However, there was no significant difference between the CochHL-Flat sub-group and the sub-groups of AN/AD for ERB2000. Also, ERB2000 was significantly different between the CochHL subgroups and between the CochHL-sub-groups and the Normal group

Table 4.24

Pairwise comparison of 'ERB2000' across the sub-groups using Mann-Whitney U test

Subgroups		AN/AD			Cochlear	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Significant $p < 0.01$	Not Significant $p > 0.05$			
Cochlear	Peak	Significant $p < 0.05$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Not Significant $p > 0.05$	Not Significant $p > 0.05$

Auditory filters were drawn based on the 'p' and 'r' values. Auditory filter shapes obtained from the different sub-groups are shown in Figures 4.3, 4.4 and 4.5.

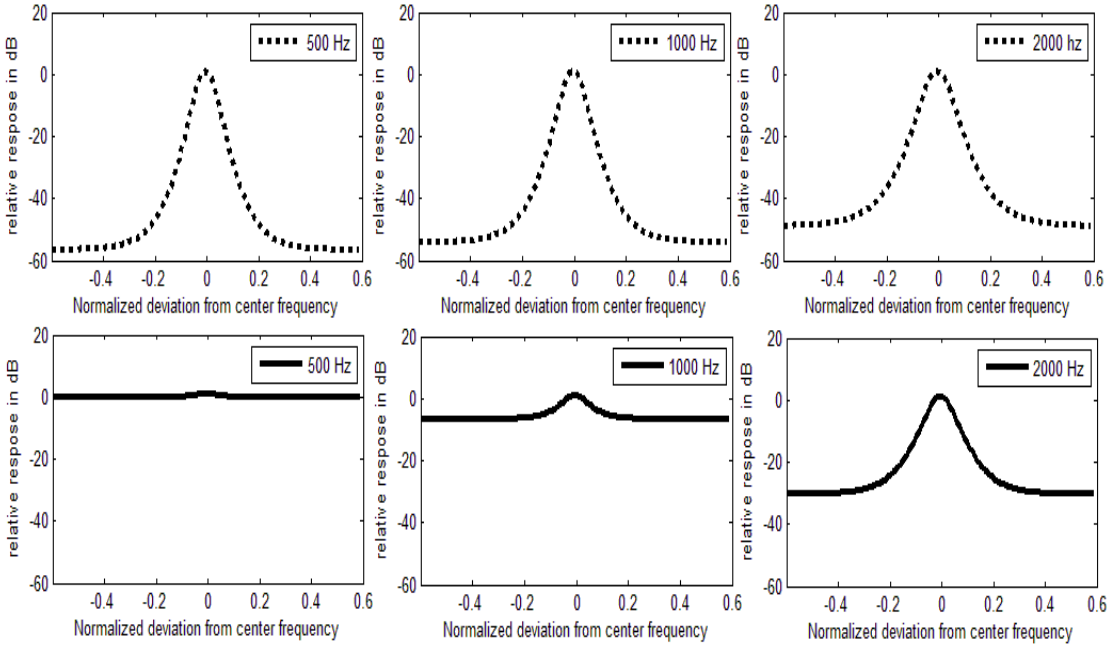

Figure 4.3. Auditory filters in normal (in the top panel) and the auditory filters in one participant from the AN/AD group (bottom panel).

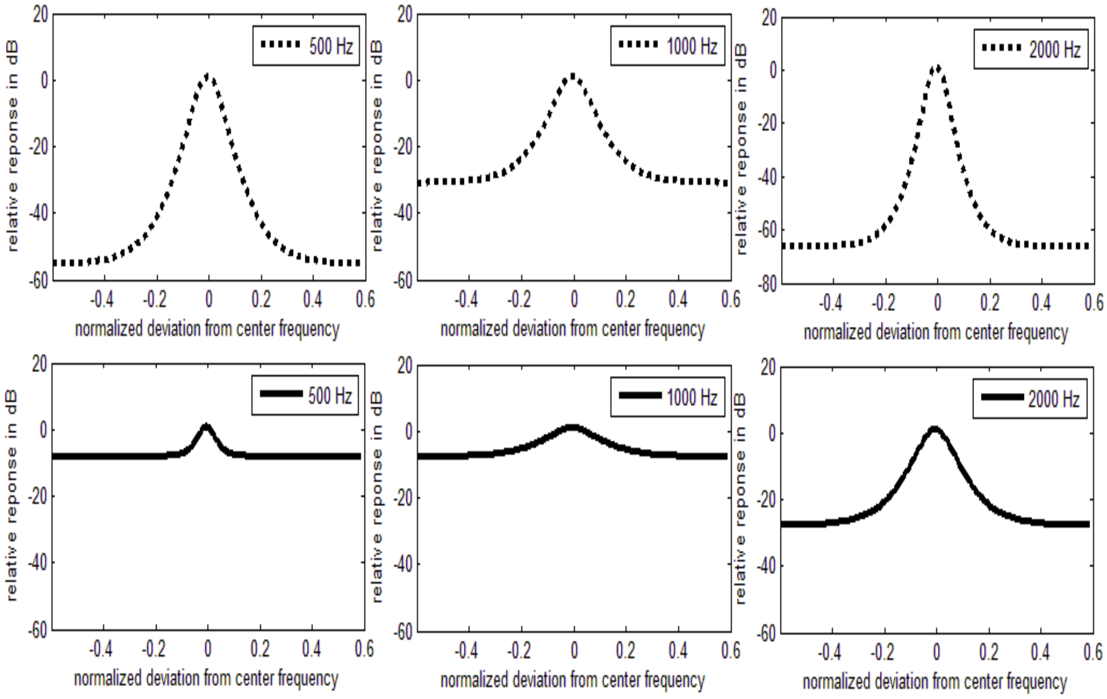

Figure 4.4. Auditory filters in the CochHL-Peak sub-group (top panel) and the auditory filters of one participant from the AN/AD-Peak sub-group (bottom panel).

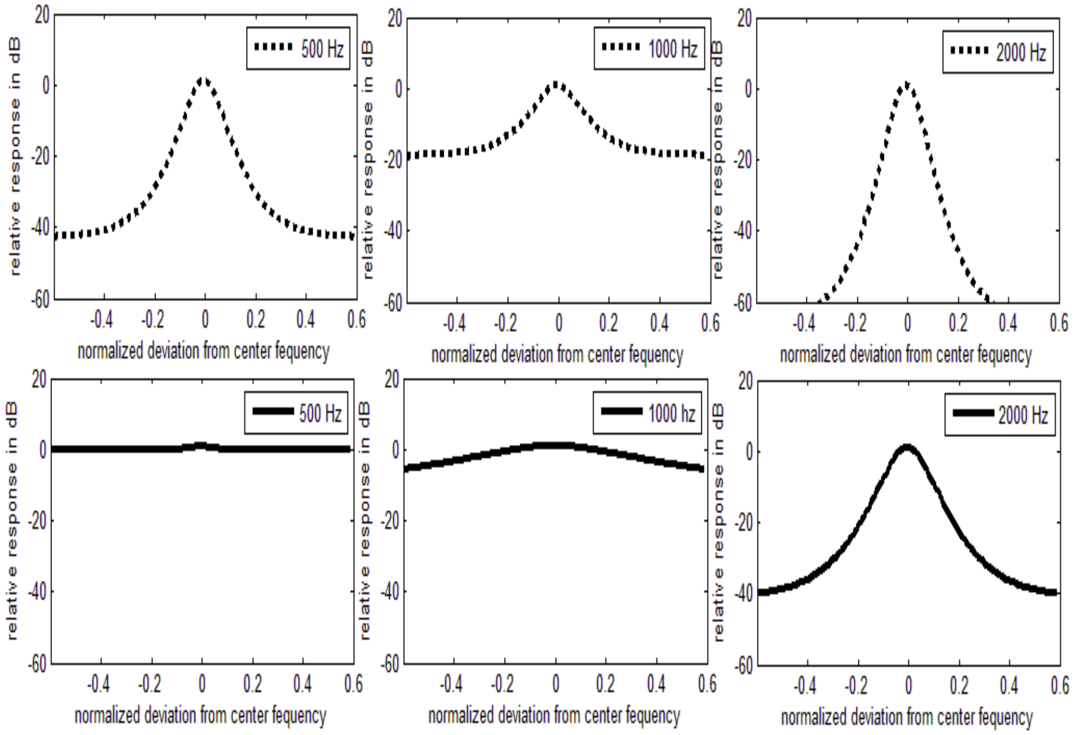

Figure 4.5. Auditory filters in the CochHL-Flat sub-group (top panel) and the auditory filters of one participant from the AN/AD-Flat sub-group (bottom panel).

4.3 Consonant Perception across the groups

Sequential information transmission analysis (SINFA) was carried out for individual consonant confusion matrices and the information transmitted for manner, place and voicing was carried out using FIX. SINFA considers the amount of information in electronic units of ‘bits’. SINFA gave the number of ‘bits’ of information transmitted for each feature out of the total information held by each feature, this was called the conditional information transmitted per feature of voicing, manner and place. The total information transmitted was also calculated. The arithmetic means and standard deviations for the conditional information transmitted for manner, place and voicing, and the total speech information transmitted in the AN/AD group, CochHL group and the Normal group are displayed in Table 4.25.

Table 4.25

Means and standard deviation of speech information transmitted in bits, in the three groups.

Groups	**Mean and S.D**	**Manner**	**Place**	**Voicing**	**Total speech information**
AN/AD	Mean	.454	.259	.189	2.903
	S.D	.184	.136	.170	.437
CochHL	Mean	.895	.729	.778	3.890
	S.D	.061	.111	.151	.196
Normal	Mean	1.000	1.000	1.000	4.322
	S.D	.000	.000	.000	.000

The Kruskal-Wallis was used for the comparison of the groups while neglecting the pattern of hearing loss is represented in the Table 4.26. Kruskal-Wallis test showed significant difference between three groups on all the speech parameters tested.

Table 4.26

Results of Kruskal-Wallis test for the comparison of transmission of manner, place voicing and total speech information in bits across the three groups.

Speech parameters	χ^2	**df**	**Asymp. Sig.**
Manner	38.499	2	.000
Place	38.493	2	.000
Voicing	37.608	2	.000
Total speech information	38.496	2	.000

Mann-Whitney U test was done to compare speech parameters across the groups in pairwise manner. Pairwise comparison showed that all the three groups were significantly different in terms of all the speech parameters tested. Table 4.27 shows the pairwise comparison of all the speech parameters across the groups.

Table 4.27

Pairwise comparison of transmission of manner, place and voicing features and the total speech information transmitted for the three groups using Mann-Whitney U test.

Groups	AN/AD	CochHL
CochHL	Significant $p < 0.01$	
Normal	Significant $p < 0.01$	Significant $p < 0.01$

The arithmetic means and standard deviations for the conditional information transmitted for manner, place, voicing and the total speech information transmitted (total speech info) for the six sub-groups are displayed in Table 4.28

Table 4.28

Means and standard deviations of conditional information transmitted for manner, place, voicing and total speech information transmitted (in 'bits') in the six sub-groups.

Sub-groups	**Mean and S.D**	**Manner**	**Place**	**Voicing**	**Total Speech info**
AN/AD Normal	Mean	.454	.263	.165	2.968
	S.D	.180	.154	.164	.398
AN/AD Peak	Mean	.392	.179	.224	2.813
	S.D	.148	.028	.227	.275
AN/AD Flat	Mean	.498	.307	.230	2.792
	S.D	.251	.124	.185	.680
CochHL Peak	Mean	.913	.813	.832	4.030
	S.D	.072	.086	.109	.225
CochHL Flat	Mean	.881	.666	.737	3.785
	S.D	.059	.085	.180	.095
Normal	Mean	1.000	1.000	1.000	4.322
	S.D	.000	.000	.000	.000

The information transmitted per feature and the total speech information transmitted was compared across the three groups using the non-parametric Kruskal-Wallis test. Kruskal-Wallis test revealed significant differences across the sub-groups of AN/AD and CochHL as shown in Table 4.29. Pair-wise comparisons were then done to check which of the sub-groups had a significant difference using the Mann Whitney U test.

Table 4.29

Results of Kruskal-Wallis test to compare the transmission of manner, place, voicing features and the total information transmitted across the sub-groups.

Speech parameters	χ^2	**Df**	**Asymp. Sig.**
Manner	38.641	5	.000
Place	38.868	5	.000
Voicing	37.747	5	.000
Total speech info	38.671	5	.000

Table 4.30

Pairwise comparison of information transmitted for manner, place and voicing and the total information transmitted across the sub-groups.

Subgroups		AN/AD			CochHL	
		Normal	Peak	Flat	Peak	Flat
AN/AD	Peak	Not Significant $p > 0.05$				
	Flat	Not Significant $p > 0.05$	Not Significant $p > 0.05$			
CochHL	Peak	Significant $p < 0.01$	Significant $p < 0.05$	Significant $p < 0.05$		
	Flat	Significant $p < 0.01$	Significant $p < 0.05$	Significant $p < 0.05$	Not Significant $p > 0.05$	
Normal	-	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$	Significant $p < 0.01$

From Table 4.30, it is evident that there was a significant difference between all the AN/AD sub-groups and the CochHL sub-groups for the transmission of manner, place and voicing features and the total speech information transmitted. The CochHL-Flat sub-group was significantly different from the Normal group for all the speech parameters however this was not seen in the CochHL-Peak sub-group.

4.4 Relation between consonant perception and temporal and frequency resolution

The relationship between temporal and frequency resolution was tested by checking the correlation between the temporal resolution parameters and consonant perception. Pearson's product-moment correlation coefficient was used to observe the correlation between consonant perception, temporal resolution and frequency resolution between the groups. Correlation within sub-groups was not performed as the sample sizes in the sub-groups were small.

Table 4.31

Pearson's product-moment correlation coefficient between temporal resolution and consonant perception in individuals with AN/AD.

Temporal resolution	Manner	Place	Voicing	Total speech information
Pk	-.522*	-.497*	-.425	-.497*
BW	.073	.196	.111	.149

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

Table 4.32

Pearson's product-moment correlation coefficients between frequency resolution and consonant perception in individuals with AN/AD.

roex parameters	Frequency resolution	Manner	Place	Voicing	Total speech information
p	p500	.043	.173	.103	.009
	p1000	-.194	-.382	-.367	-.207
	p2000	.183	.268	.198	.247
r	r500	.282	.346	.222	.145
	r1000	-.655**	-.703**	-.667**	-.704**
	r2000	-.275	-.160	-.164	-.272
ERB	ERB500	-.522*	-.474*	-.644**	-.486*
	ERB1000	-.442	-.207	-.182	-.334
	ERB2000	.047	.026	.149	-.176

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

Pearson's product-moment correlation showed a significant negative correlation between the Pk and the manner and place features. There was a significant negative correlation between ERB500 and the manner, place and voicing features. There was a significant negative correlation between r1000 and the manner, place and voicing features. The total speech information transmitted had a significant negative correlation with Pk, ERB500 and r1000. However, there was no significant correlation between the other temporal and frequency resolution parameters with that of the speech parameters. To understand better about the relation between the different parameters and the perception of consonant features, scatter plots have been drawn which can be seen in Figures 4.6, 4.7 and 4.8.

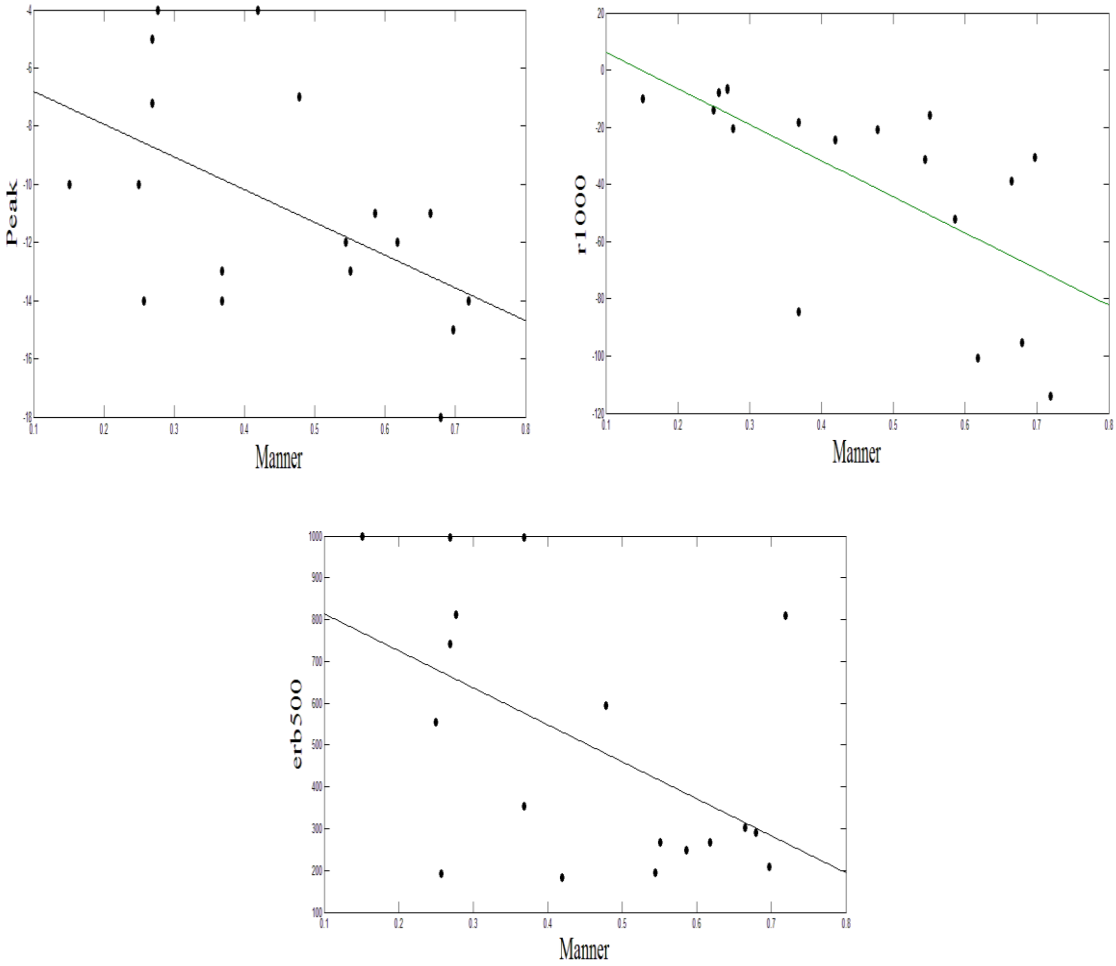

Figure 4.6. Scatter plot of manner feature with Pk, r1000, and ERB500

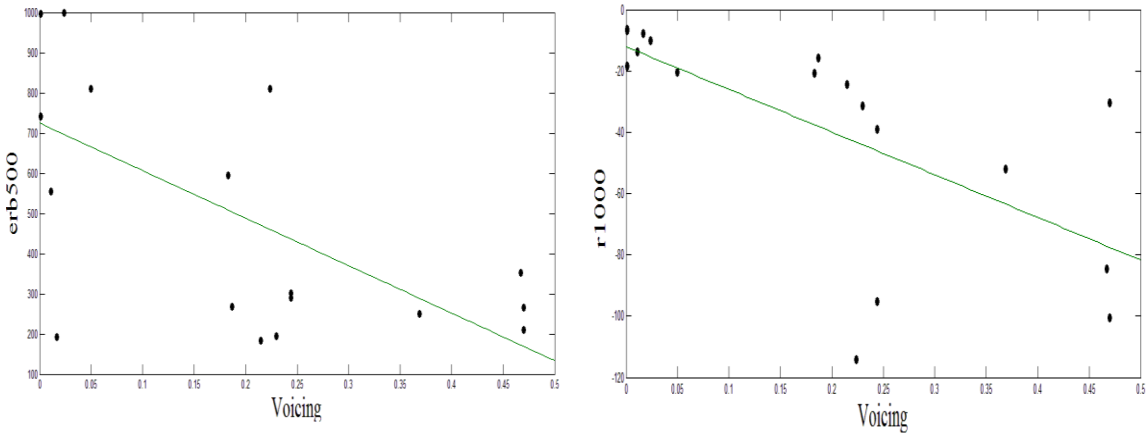

Figure 4.7. Scatter plot of voicing feature against ERB500 and r1000

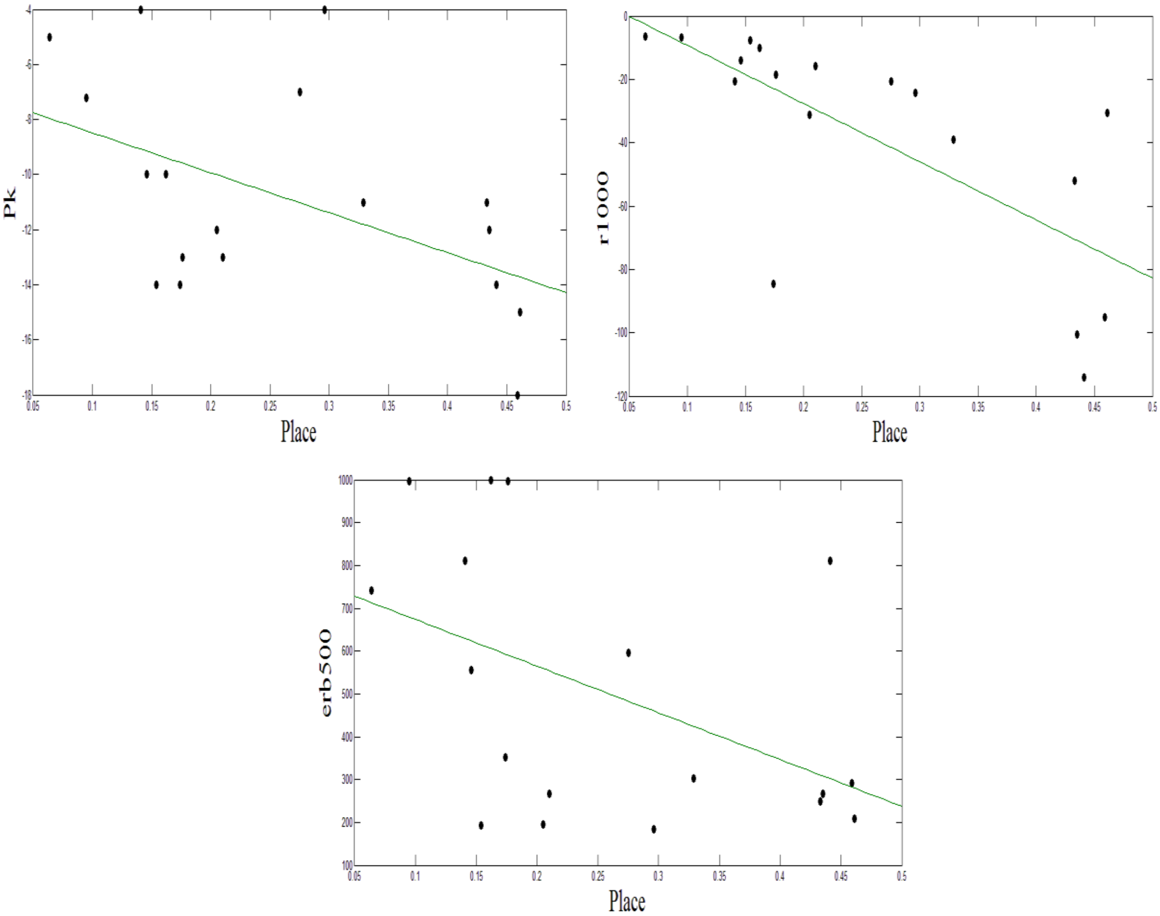

Figure 4.8. Scatter plot of place feature against Pk, r1000 and ERB500

Linear regression analysis was carried out to construct a model to predict the speech parameters based on frequency resolution and temporal resolution obtained in individuals with AN/AD. A least squares design was considered for fitting of the model. For the derivation of the model for manner and place the ERB500 and Pk and r1000 were considered and for the derivation of the model for voicing the ERB500 and the r1000 were considered. Only the above mentioned parameters were considered for the regression analysis as these were the parameters which showed significant correlation with the consonant perception measures. The regression analysis was carried out by fitting a range of linear equations (models) to the data, with the speech parameters as the dependent variables and the temporal and frequency resolution parameters as the independent variables. The models with the highest r-square value were chosen and have been given below.

The model for predicting manner information transmitted in bits per feature based on ERB500 and Pk is as in equation 4.1. The model had an R-square value of 0.581 with F(3,14) = 6.462 at p = 0.006.

$$Manner = 0.39102 - (0.0066 \times Pk) - (0.00021 \times erb500) - (0.0025 \times r1000)$$

….equation 4.1

The place feature was also fitted with a model based on the ERB500, r1000 and Pk using a least squares method as shown in equation 4.2 to predict the place information transmitted in bits per feature. This model had an R-square value of 0.597 with F(3,14) = 6.904 at p = 0.004.

$$Place = 0.20892 - (0.00013 \times erb500) - (0.00225 \times r1000)$$

…equation 4.2

The model for predicting voicing feature based on ERB500 and r1000 is as in equation 4.3. The model had an R-square value of 0.691 with F (2, 15) = 16.808 at p = 0.0001.

$$voicing \ = \ 0.22890 - (0.00028 \times erb500) - (0.00260 \times r1000)$$

…Equation 4.3

Figure 4.9 shows the fitted model plot for the voicing feature based on ERB500 and r1000. The dark shaded region shows the prediction region of the model for the voicing based on ERB500 and r1000. The dots represent the voicing feature transmitted across the ERB500 and r1000 for each subject.

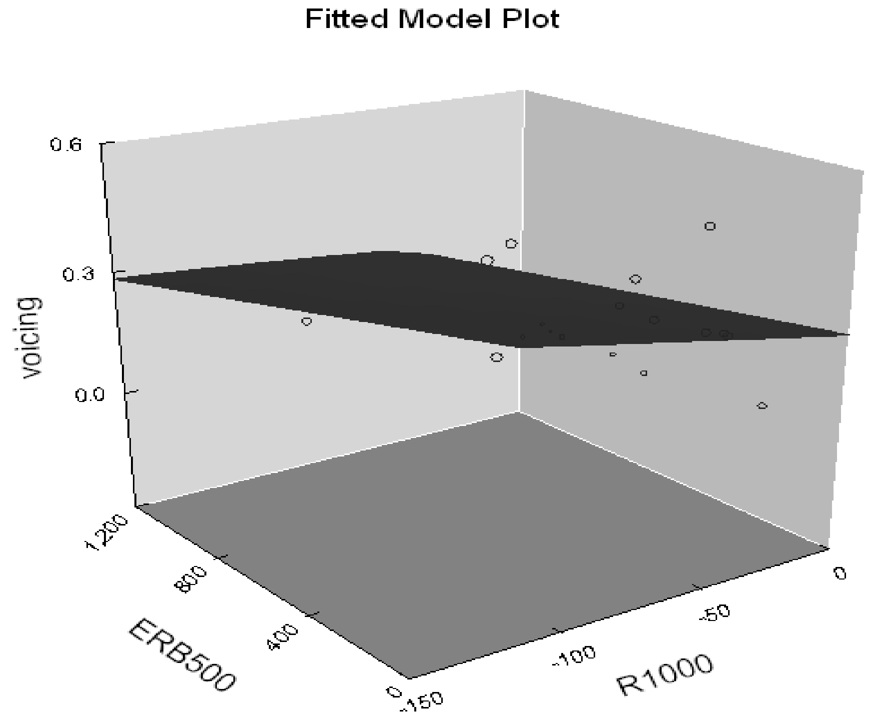

Figure 4.9. Fitted model plot of voicing based on ERB500 and r1000

Chapter 5

Discussion

5.1 Temporal resolution

The mean TMTF had a low pass shape in the Normal group and the CochHL-Flat sub-group, whereas, all the AN-AD subgroups and the CochHL-Peak had a TMTF which was band pass in shape. The mean modulation detection thresholds were the best in the Normal group followed by the CochHL hearing loss group and least in the AN/AD group. Comparison across the groups showed that the AN/AD group had significantly lower peak sensitivity and bandwidth compared to the Normal and CochHL group. There was no significant difference between the peak sensitivity of the normal and the CochHL group. However, the bandwidth of the TMTF was significantly lower in the CochHL group compared to the Normal group.

Comparison across sub-groups of AN/AD showed that there was no difference between the sub-groups of AN/AD for the both peak sensitivity and bandwidth of the TMTF. This finding implies that the temporal peak sensitivity and bandwidth of the TMTF in the AN/AD group is not dependant on the audibility factor, as the sub-groups of AN/AD had different audiometric patterns yet they had similar TMTFs. The TMTFs in our study were measured at a constant Intensity level of 65 dB SPL and if there were any difference in the modulation sensitivity because of the effect of audibility it would have shown as a difference in peak sensitivity and bandwidth across the sub-groups of AN/AD.

The CochHL-Peak and CochHL-HL-Flat sub-groups were not significantly different from that of the Normal group in terms of the peak sensitivity of the TMTF.

However, the bandwidth in CochHL-Flat subgroup was significantly lower (BW = 55.85) than that of the Normal group. But, the bandwidth in the CochHL-Peak (53.67) was not significantly different from the Normal group. The lower bandwidth in the CochHL flat group can be explained in two ways. The first being disrupted gross temporal resolution because of the cochlear damage and the second explanation being the effect of audibility. Bacon and Viemeister (1985) and Formby and Muir (1982) have shown that individuals with cochlear hearing loss had poorer sensitivity for detecting the modulations at higher modulation rates. The reasons they cited was the poorer audibility at the high frequency regions in the cochlea i.e. the higher frequency regions are more responsible for providing the accurate temporal envelope information as they have lesser inherent fluctuations. Moore (2007) also reported the same as above and concluded that the reduced temporal resolution in cochlear hearing loss is because of the reduced audible bandwidth, and when this was increased by increasing the sensation level, then individuals with cochlear hearing loss performed similar to that of the normal hearing listeners. This would give weight to the second explanation causing reduction in the bandwidth of the TMTF in the CochHL group. The CochHL-Peak subgroup did not show any significant difference from that of the normal group. It would be convenient to assume that this finding could have been because of the better hearing in the high frequencies in this sub-group, but it should be noted that the mean bandwidth in this sub-group was lower than that of the CochHL-Flat subgroup. This discrepancy can be attributed to the higher standard deviation in the CochHL-Peak which might have masked any difference and similarities in the TMTF between this sub-group and the Normal group.

The comparison of the AN/AD group with that of the cochlear group showed that the peak sensitivity and bandwidth of the TMTF are significantly lower in the

AN/AD group. This is in accordance to Zeng et al. (1999, 2005), Rance et al. (2008) and Kumar and Jayaram (2005). This can be attributed to the well-established fact that AN/AD is a predominantly timing related disorder because of loss of neural synchrony which affect temporal resolution markedly (Starr, 1996 ; Starr et al., 1999; Zeng et al., 1999, 2004; Rance, 2004; Rance eta al., 2008). Thus, temporal resolution is clearly different in cochlear hearing loss and auditory dys-synchrony.

The bandwidths of the TMTFs obtained in this study are in accordance with that of Formby and Muir (1988) and Eddins (1993) but do not go along with the bandwidths measured by Zeng et al. (1999). Zeng et al. (1999) obtained a mean bandwidth of 237 Hz in normal hearing listeners as opposed to a mean of 72 Hz in the current study. This might be because of the use of larger frequency intervals used by Zeng et al. (1999) which might have smoothened off the TMTF and overestimated the bandwidth.

It is evident from the TMTF that the low modulation frequencies and the high modulation frequencies are more affected hence, giving the TMTF a band pass shape in those with AN/AD as opposed to the low pass shape in normal hearing listeners. . All in all, individuals with AN/AD had poorer temporal resolution abilities irrespective of the audibility factor compared to cochlear hearing loss, in whom temporal resolution abilities are affected by the audibility fact.

5.2 Frequency resolution

The parameters r500, ERB500, ERB1000, p2000, and ERB2000 were the ones which were significantly different across the sub-groups. The parameter r500 which decides the tails of the auditory filters, was significantly higher in the individuals with AN/AD which indicates at a steep tail of the auditory filter compared to the normal hearing individuals. However, the slope of the tail of the auditory filter at 500 Hz was not significantly different from that of the cochlear hearing loss group. This increased slope of the tail of the auditory filters in the AN/AD groups would lead to greater susceptibility to masking from spectral components even far away from the centre frequency. The mean equivalent rectangular bandwidth (ERB) at 500 Hz was nearly four times that of the normal hearing group and the cochlear loss with peak sub-group. This was evidenced even in the raw notched noise data as no shift or 5 to 10 dB shift in threshold of detection of the tone, obtained in the notched noise even after varying the notchwidth in most of the individuals with AN/AD. The ERB at 500 Hz in the sub-group with flat cochlear hearing loss was higher than that of the normal group and the sub-group of cochlear hearing loss with peak at 2 kHz. The bandwidth of the auditory filter in AN/AD was not significantly different across sub-groups, this implies that the pure-tone thresholds and the audiometric patterns were not the major reasons for the poorer frequency resolution abilities. The equivalent rectangular bandwidth at 1000 Hz was three and a half to four times greater in individuals with AN/AD compared to normal hearing listeners, which means that individuals with AN/AD have very broad auditory filters at 1000 Hz. But ERB at 1000 Hz in the AN/AD group was similar to that of the cochlear group. Additionally ERB at 1000 Hz in the cochlear hearing loss sub-group with mild flat hearing loss was greater than ERB seen in the normal group. This finding indicates at similarities in the frequency resolution between the cochlear hearing loss sub-group with a peaked audiogram and AN/AD group at 1000 Hz.

Findings similar to the raw notched noise data in the current study was reported by Kraus et al. (2000) where they found only a 3 dB change in threshold for change in notchwidth to 0.25 from 0.00. They attribute this factor to the over masking effect taking place in individuals with AN/AD as explained by Zeng et al. (2005). This small threshold shift with increase in notchwidth is what is seen even in individuals with cochlear hearing loss with broadened auditory filters i.e. individuals with broadened auditory filters show very small change in the masked threshold with changes in the notchwidth (Glasberg & Moore, 1986). Though, this was not cited as one of the possible reasons for the results reported by Kraus et al. (2000), the results of this study suggest that this small change in threshold seen in individuals with AN/AD at 1000 Hz is because of the broadened auditory filters.

The parameter p2000 depicts the slope parameter ‘p’ which describes the slope of the tip of the auditory filter (nearly the upper half of the auditory filter). This slope of the auditory filter tip was significantly shallower in the subgroups of AN/AD with flat hearing loss when compared to the normal group. But the other groups of AN/AD had ‘p’ similar to that of normal. This implies that the AN/AD subgroup with flat hearing loss had a shallower tip in their 2000 Hz auditory filter. This would imply that the slope of the auditory filter at 2000 Hz was related to the absolute threshold at 2000 Hz in the AN/AD group. The slope of the auditory filter at 2000 Hz in the cochlear hearing loss group with peak at 2000 Hz was also shallower compared to the normal group. However, the same was not noticed in the cochlear hearing loss sub-group with flat hearing loss. This indicates that shallower auditory filter tips are not necessarily related to the absolute thresholds in individuals with cochlear hearing loss.

The ERB at 2000 Hz in the AN/AD group was nearly one and half to two times that of the 2000 Hz ERB in the normal group. The ERB at 2000 Hz in AN/AD subgroup with flat hearing loss was significantly larger than ERB at 2000 Hz in the other AN/AD subgroups with lesser degrees of hearing loss. This shows a relation between the absolute threshold and the frequency resolution in AN/AD for 2000 Hz.

And it was also seen that there was no difference in ERB at 2000 Hz for all AN/AD sub-groups compared to the cochlear hearing loss sub-group with flat audiometric pattern. This points towards similarities in the frequency resolution abilities between the cochlear hearing loss group and the AN/AD sub-groups for the higher frequencies.

The results of frequency resolution showed broader auditory filters at lower frequencies compared to the higher frequencies in individuals with AN/AD. This might also be the additional reason why the DLFs at lower frequencies are more impaired compared to the higher frequencies as seen in Zeng et al (2005) and Barman (2008) apart from the explanation of place and temporal coding.

The results of the study showed poorer frequency resolution at 500 Hz through 2000 Hz in individuals with AN/AD. Though AN/AD is reported in literature to be a significantly timing related deficit the results of the current study indicate that temporal resolution deficits coexist with frequency resolution in individuals with AN/AD. These results could be supported with findings of Starr et al. (2003) where they found 30 % loss of outer hair cells in the apical turns of the cochlea in an individual with AN/AD. This suggests that individuals with AN/AD might have a dysfunction right at the level of the cochlea which might hamper the frequency selectivity. However, the results of the current study and that of Kraus et al.(2000) are not in accordance with the that of Rance, McKay and Grayden (2004) where they reported no difference in the threshold shift between a notched noise and a broadband noise across normal hearing listeners and individuals with AN/AD. This might be the consequence of the difference in procedure used, i.e. the masker stimuli were similar in the current study and Kraus et al. (2000), and however, Rance, McKay and Grayden (2004) used broadband noises (with and without notch) as maskers and also used a low intensity pink noise in their normal hearing listeners to simulate the effect of the elevated threshold.

5.3 Consonant perception

The results of consonant perception evaluation show that AN/AD group had the most difficulty in perception of manner, place and voicing compared to the cochlear hearing loss group. Voicing feature was perceived the least, followed by place feature and manner was the best perceived feature. However, in the cochlear hearing loss group, manner feature was the best perceived followed by voicing and place features. Manner was the best perceived feature in both AN/AD and the cochlear hearing loss groups. There was no difference in the perception of manner, place and voicing across sub-groups of AN/AD. This implies that there was no relationship between the audiometric pattern and speech perception in individuals with AN/AD. The consonant perception results are in accordance with reports by Rance et al. (2008), Narne and Vanaja (2008). They reported that the voicing errors are the predominant errors in AN/AD followed by place and manner errors.

5.4 Relationship between consonant perception and temporal and frequency resolution.

The analysis of correlation between consonant features perceived and the temporal and frequency resolution parameters showed significant correlation between the consonant features perceived and the temporal and frequency resolution in individuals with AN/AD. The perception of Place and manner features correlated significantly with the peak sensitivity of the TMTF. This implies that individuals with AN/AD are not able to utilise the temporal cues which are important for the perception of manner and place cues. The temporal parameters which are most important for the perception of manner cues are the consonant duration and the temporal envelope. And any deficits in the temporal resolution would thus hamper the perception of the manner feature. The important temporal parameters important for perception of place features are the rapid formant transitions which are again impaired because of the temporal resolution (especially the fine structure coding) deficit. The voicing feature however did not correlate with temporal resolution deficit. This however is in contrast to the results of Rance et al. (2010), wherein they reported good correlation between the perception of voicing feature and the gap detection threshold. This would mean that, the VOT might not have been an important cue, in the stimuli used in this study which were VCV combinations. This is in fair accordance with the results of Narne and Vanaja (2008) where they reported negligible improvement in the voicing perception after temporal envelope enhancement. They explain this by saying that the envelope enhancement changes the depth of the temporal envelope enhancing the voice onset time. They conclude that envelope enhancement does not bring about changes in the voicing bars and the first formant frequency and thus, the perception of the lower frequencies is important for voicing perception.

The errors in consonant feature perception for manner and place correlated with the frequency resolution parameter r1000 and ERB500. This implies that the errors in perception of the consonant features significantly correlated with the tail of the 1000 Hz auditory filter and the bandwidth of the 500 Hz auditory filter. The broader tail of the auditory filter at 1000 Hz might have led to increased susceptibility to the spread of masking, and poorer resolution of important spectral components of the speech sounds on the basilar membrane. The important frequency related parameters for perception of place feature are consonant spectrum, formant transition and formant frequencies of the preceding and succeeding vowels in a VCV combination. Affected place feature perception is also a consequence of significant frequency resolution deficit in the AN/AD group in the current study. This is in accordance to studies by Thibodeau Van Tasell (1987), Preminger and Wiley (1985) and Turner and Henn (1989) in individuals with cochlear hearing loss, and they attributed the poorer speech perception (place and manner) to affected frequency selectivity.

The voicing feature correlated with the bandwidth of the auditory filter at 500 Hz and the slope of the tail of 1000 Hz auditory filter, and not the temporal resolution deficit. This could be because of the fact that the voicing murmur was probably the greater cue in the VCV stimuli used in our study compared to the voice onset time. Thus, this voicing murmur cue could have significantly affected by the frequency resolution at low frequencies as the voicing murmur is a low frequency cue. This is in accordance to the findings of Narne and Vanaja (2008).

Regression analysis of the relationship between manner and feature perception and frequency and temporal resolution was carried out to fit a model to investigate the extent of relationship between frequency and temporal resolution as shown in equations 4.1, 4.2 & 4.3. The model clearly gives lesser weightage to the bandwidth of the 500 Hz auditory filter and greater weightage to peak sensitivity of the TMTF and greatest weightage to the tail of the 1000 Hz auditory filter for the place and manner perception. The peak sensitivity had greatest weightage for the place perception, followed by r1000 and ERB 500. However, this model should be used with caution, as a linear model has been fitted for the data only for ease of calculation and this does not guarantee hundred per cent prediction accuracy.

Chapter 6

Summary and Conclusions

The most striking feature in auditory dys-synchrony (AN/AD) is the severely degraded speech perception abilities in the presence of relatively spared audibility. The speech perception in Auditory Dys-synchrony has been studied mainly with respect to the scores. The speech perception scores as such do not give much information about which speech sounds are being perceived and which speech sounds are not being perceived or not being perceived clearly by an individual. Analysis of the pattern of errors in speech perception would give us a better picture about the speech perception abilities of an individual. There are a very few studies which have studied in detail about the pattern of speech errors in individuals with AN/AD and they have reported that the perception of voicing was the most affected followed by place and manner perception, wherein manner perception was better than place perception (Narne & Vanaja, 2008; Rance et al. 2010). The pattern of speech errors have been studied in relation to frequency discrimination and gap detection (a measure of temporal resolution) and modulation detection thresholds for modulation frequencies of 10 Hz 50 Hz and 150 Hz by Rance et al. (2010). However, this has not been studied in relation to frequency resolution and the complete temporal modulation transfer function (TMTF) with slow and fast modulation frequencies (representative of the temporal modulations in speech) which is a more comprehensive measure of temporal resolution. Literature has shown that there is a marked deficit in the temporal resolution in individuals with AN/AD based on the TMTF but there are only a handful of studies which have compared the TMTF with the speech perception abilities (Kumar & Jayaram, 2005; Rance et al., 2010, 2008). The frequency resolution abilities in individuals with AN/AD are not well agreed upon in literature (Rance, McKay & Grayden, 2008; Vinay & Moore, 2007; Kraus et al., 2000), however the methods used in these studies were affected by the use of broadband notched noise along with a pink noise, the occurrence of beats and off-frequency listening and the limited notchwidths used respectively. It is thus necessary to study the effect of frequency resolution abilities in more controlled manner. And it is important to study the relation between the frequency and temporal resolution abilities with the pattern of speech errors in individuals with AN/AD.

Thus, the main purpose of the study was to observe the pattern of errors in consonant perception, frequency resolution and temporal resolution and to study the dependence of consonant perception on the frequency and temporal resolution abilities in individuals with auditory dys-synchrony. Additionally, the study aimed at investigating the similarities and differences in consonant perception, frequency resolution and temporal resolution abilities in individuals with AN/AD and cochlear hearing loss.

A total of eighteen ears with AN/AD were considered for the study out of which eleven ears had hearing sensitivity within normal limits, three ears had mild low frequency hearing loss with peak at 2 kHz, and the remaining four ears had a mild flat hearing loss. Seven ears with cochlear hearing loss matched to the severity of hearing loss and the audiometric pattern were considered as controls for the seven ears of AN/AD with hearing loss. Eighteen normal hearing ears with no history of otological or neurological problems and no complaint difficulty understanding speech in the presence of noise were considered as controls for the remaining eleven ears with AN/AD.

The temporal resolution in the study was analysed by measuring the sinusoidal amplitude modulation detection thresholds for modulation frequencies of 2 Hz, 4 Hz, 8 Hz, 16 Hz, 32 Hz, 64 Hz, 128 Hz, 256 Hz, and 512 Hz at a level of 65 dB SPL. This gave the temporal modulation transfer function, and from this the peak sensitivity and the bandwidth were calculated to quantify the temporal resolution abilities.

The frequency resolution was assessed at frequencies of 500 Hz, 1000 Hz and 2000 Hz using a notched noise method recommended by Glasberg and Moore (1990). The notches in the current study were symmetrically spaced around the centre frequency with notchwidths of 0.0, 0.1, 0.2, 0.3, 0.4 and 0.5. The pure tone thresholds for 500 Hz, 1000 Hz and 2000 Hz pure tones measured in the presence of their respective maskers at all the notchwidths at a noise spectrum level of 50 dB SPL/Hz. The auditory filters were derived from the notched noise data obtained and the slope of the auditory filters and the equivalent rectangular bandwidths were calculated.

The consonant perception was analysed by assessing the closed set perception of VCV (vowel-consonant-vowel) combinations. The resulting consonant confusion matrices were analysed for the extent of perception of manner, place and voicing features using information transfer analysis.

The data obtained from the above mentioned experiments were subject to statistical analysis. Kruskal-Wallis test was performed to check for significant difference between variables across groups. Mann-Whitney U test was used to check the groups which were significantly different for the parameters which showed significant difference on the Kruskal-Wallis test. Pearson’s product-moment correlation was carried out to check for the correlation between the manner, place and voicing information transmitted with the frequency and temporal resolution measures.

Finally linear regression analysis was done to arrive at a model to explain the effect of temporal and frequency resolution on perception of speech features.

The results obtained after statistical analysis of all the parameters for the three groups of subjects are summarised below.

- Individuals with AN/AD had significantly lower peak sensitivity of the TMTF compared to the normal hearing group and the cochlear hearing loss group. The peak sensitivity of the TMTF in the normal hearing group and the cochlear hearing loss group was similar. The bandwidth of the TMTF in AN/AD group was significantly reduced compared to the normal hearing group and cochlear hearing loss group. The bandwidth of TMTF in the cochlear loss group was significantly reduced compared to the normal hearing group, but was significantly higher than that of the AN/AD group.
- Individuals with AN/AD had significantly broader auditory filters compared to the cochlear hearing loss group and the normal hearing group for the frequencies of 500 Hz, 1000 Hz and 2000 Hz. The Auditory filters at the low frequencies were broadest (4 times normal ERB) compared to the higher frequencies (2 times the normal ERB at 2000Hz). The auditory filters in AN/AD were broader than that of their matched controls with cochlear hearing loss for 500 Hz. However there was no difference between auditory filters at 1000 Hz and 2000Hz in the cochlear hearing loss group with a flat audiometric configuration and the AN/AD sub-groups .
- Voicing errors were the most dominant followed by place errors and manner errors in AN/AD compared to predominant place errors in cochlear hearing loss followed by voicing and manner errors.

- A significant correlation between frequency resolution at 500 Hz and 1000 Hz, and the peak sensitivity of the TMTF with the perception of manner and place features of the consonant was also found.
- There was a significant correlation between the frequency resolution at 500 Hz and 1000 Hz and the perception of voicing features of consonants.
- Models have been derived depicting the relationship between speech perception, frequency resolution and temporal resolution for the voicing feature, place feature and manner features

This study shows that the auditory filters in individuals with AN/AD are affected more in the lower frequencies compared to the higher frequencies which is consistent with the poorer perception of low frequency cues (Zeng et al. 2005; Rance 2005). The temporal resolution is significantly affected in individuals with AN/AD which might be attributed to the poor neural phase locking in individuals with AN/AD (Starr et al., 1999). The temporal and frequency resolution measures had a significant correlation with the perception of manner and place feature perception which point towards the fact that the affected speech perception in individuals with AN/AD is because of the combined effect of impaired frequency and temporal resolution. However, the voicing perception was significantly correlated with the frequency resolution at the low frequencies which points out to the fact that the poorer voicing perception in these individuals is because of the poor processing of low frequency information.

Conclusions

It can be concluded from the current study that the frequency and temporal resolution are affected in individuals with AN/AD and this deficit is greater than what is seen in individuals with cochlear hearing loss. The errors in the perception of place and manner features in individuals with AN/AD are because of inefficient processing of the temporal cues in speech and the inefficient processing of the lower frequency components of speech. The voicing related errors in speech perception in individuals with AN/AD is primarily due to inefficient processing of the lower frequency information in the speech signal in the VCV combinations used in the study.

Implications of the current study

- The results of this study help in understanding the temporal and frequency resolution abilities in individuals with auditory dys-synchrony.
- The results of the study help to understand the specific speech perception deficits and abilities in individuals with auditory dys-synchrony.
- Thus, the outcome of this study can be used to assess the communication ability in individuals with auditory dys-synchrony.
- The results of this study provide valuable information which could be used to modify the rehabilitation strategies in individuals with auditory dys-synchrony.
    - This information might help in modifying the hearing aid technology to meet the special needs of individuals with auditory dys-synchrony.

- Might also help in modifying the speech processing strategies in cochlear implants to suit the requirement of individuals with auditory dys-synchrony.

Limitations of the current study

- The frequency resolution was studied using symmetrically placed notches in the current study, which does not give information about the lower and higher skirts of the auditory filters separately. Use of asymmetrically placed notches would have given more information about the frequency resolution abilities and the susceptibility to masking. Also the ERB for 500 Hz and 2000 Hz in the current study is higher than that predicted by the ERB but is in accordance with Glasberg and Moore (1986) this could be due to the method used and also the higher masker level used.
- The notched noise stimuli used for assessment of frequency resolution were generated by the filtering of a broadband noise. This procedure leads to minor irregularities in the noise spectrum which might affect the study results. The more efficient way of generating the noise stimuli with minimal spectral irregularities is by adding multiple closely spaced sine waves with random phases.
- Each speech stimuli in the current study were presented three times, but for stronger results from the information transfer analysis it is suggested that each stimuli be presented more than ten times each. But this could not be followed in the current study due to the fact that the whole experiment took a lot of time to administer as increasing the number of presentation of the speech stimuli would significantly increase the testing time.

- The small sample size in the sub-groups of AN/AD, and the cochlear hearing loss groups restricted us from comparing the psychoacoustic measures and the speech perception measures.

Future directions of research

- Speech perception in relation to the temporal fine structure and envelope coding and the frequency selectivity in individuals with AN/AD would give a more comprehensive picture about the speech perception in such population.
- Speech perception abilities in noise and its relation to the temporal and frequency resolution parameters would help to know the specific deficits in individuals with AN/AD in the presence of noise.
- Use of spectrally sharpened stimuli in individuals with AN/AD could be another avenue to explore as these individuals also have poorer frequency resolution.
- The current data on AN/AD can be used for simulation of affected frequency and temporal resolution in individuals with AN/AD. The simulation studies in AN/AD as of now have only focussed on the temporal processing deficits. The simulation of frequency resolution deficit along with the temporal processing deficits might help to simulate the perception of individuals with AN/AD in a better manner.
- It would be intriguing to study the frequency resolution abilities in individuals with AN/AD at even higher frequencies.
- It would be interesting to study the effects of level on the frequency selectivity in AN/AD, which would give more insight into the functioning of the cochlear outer hair cells in individuals with AN/AD.

Chapter 7

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Appendix I

The modification in the psychoacoustics toolbox to conduct the notch noise masking experiment is described below. First download the Psycho-acoustics toolbox and prepare the below mentioned two m files and place them in the respective folders.

The below written code should be saved with a file name stereo_masking.m and should be placed in the Experiment_S folder of the Psychoacoustic toolbox

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%

function [pos_ans, q] = stereo_masking(std_level, var_level, nAFC)
%%
%%this program has been written to conduct simultaneous notched noise
%%masking test to derive the auditory filters, the noise and tone has
%%to be routed through separate channels of an audiometer or
%%programmable attenuator (PA5 of TDT) and have to be mixed using an
%%SM5  mixer or to the same side using a two channel audiometer.

sf = 44100; % sample frequency in Hz
signaldur = 300; % signal duration
freq = 2000; % signal frequency
noisedur = 400;% noise duration
notchwidth = 0.5; %normalized notch width
lf = freq-notchwidthfreq; % noise lowest frequency
hf =freq+notchwidthfreq; % noise highest frequency

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
noiselevel = 50;
signalaamp = var_level;
dBs = 100 - signalaamp;
dBn = 100 - noiselevel;
% [1] %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GENERATE SOUNDS
signal = GenerateTone(sf, signaldur, freq);
signal = GenerateEnvelope(sf, signal);
signal = signal/max(abs(signal));

signalS = AttenuateSound(signal,-dBs);
signalN = AttenuateSound(signal,-dBn); %%% the reference tone for
setting the amplitude

referenceN = max(abs(fft(signalN)));

signal_fin = 8signalS;
noise = GenerateNoise(sf, noisedur, 'notched', lf, hf);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
%Limiting the passbands on either sides of the noise to 0.8times freq
```

```
    noise1=noise;                                  % Nyquist
frequency
    numberofsamples = length(noise1);     % number of samples
    dur= (numberofsamples/sf)1000;
    % half number of samples
    % make noise

    %
=====================================================================
====
    % set variables for filter
    Lp = (freq - 0.8freq)  (dur/1000); % lf point in frequency domain
    Hp = (freq + 0.8freq)  (dur/1000); % hf point in frequency domai

    filter = zeros(numberofsamples, 1);
            filter(Lp : Hp, 1) = 1;
            filter(numberofsamples - Hp : numberofsamples - Lp, 1) =
1;

    noise1 = fft(noise1);                 % FFT
    noise1 = noise1 . filter;
    noise1 = ifft(noise1);                % inverse FFT
    noise1 = real(noise1);
    % amplitude normalization
    noise = noise1/max(abs(noise1));
    noise = noise.999;

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


noise = GenerateBandNoise (sf, noise,freq-0.8freq,freq+0.8freq);
noise = GenerateEnvelope(sf, noise);
ampn = referenceN;
noise1 = fft(noise)/max(abs(fft(noise))); %% Normalization in the FFT
domain
noisea = ampnnoise1;                     %% multiplying the noise
with the reference amplitude
noise_fin  = 8ifft(noisea);            %inverse fft
s_t=(length(noise_fin)-length(signal_fin))/2;
silence=zeros(s_t,1);
signal_fin=[silence;signal_fin;silence];

variable = AddTwoSounds(sf, noise_fin, signal_fin);%AddTwoSounds(sf,
noise_fin, signal_fin);

standard = noise_fin;
% [2] %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% RANDOMIZE POSITION OF STANDARD AND VARIABLE AND SET, ACCORDINGLY,
THE KEY
% THE SUBJECT HAS TO PRESS TO GIVE A CORRECT RESPONSE
if ~nAFC
    pos_ans = 1;
    sequence = variable;
else
    [sequence, pos_ans] = ShuffleSounds(sf, standard, variable, 3);
end;
% [3] %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLAY THE SOUND
sound(sequence, sf, 16);
```

```
% [4] %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ASK THE QUESTION TO THE SUBJECTs
if ~nAFC
    q = 'Can you hear the signal ("1") or not ("0")?: ';
else
    q = ['Where was the signal (' num2str(1:nAFC) ')?: '];
end;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

The below written code has to be saved with a file name stereo_maskingPar_S.m in Matlab and should be placed in the Defaults_S folder in the psychoacoustics toolbox

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function    stereo_maskiPar_S(mh)
set(mh.nblocks,'String',    1   );
set(mh.fileout,'String','0.02.txt');
set(mh.startinglevel,'String',  70  );
set(mh.standard,'String',   -Inf    );
set(mh.reversals,'String',  '2 5 ');
set(mh.stepsize,'String',   '10 2 ');
set(mh.NameStepsize,'String', 'Step Size');
set(mh.stepbutton,'value',1 );
set(mh.TwoDownOneUp,'value',1   );
set(mh.Arithmetic,'value',1 );
set(mh.nafcbutton, 'value' ,1);
set(mh.textnafc,'Visible','on');
set(mh.nafc,'Visible', 'on');
set(mh.nafc, 'String' ,     3   );
set(mh.reversalForthresh,'String',  5   );
set(mh.feedback, 'value' ,  1   );
set(mh.SaveResults, 'value' ,   1   );
```

%%%%%%%%%%%%%%%%

After placing the above mentioned files in their respective folders, add the whole psychoacoustics toolbox to the Matlab path . Then open the psychoacoustics folder from Matlab and type "staircase" in the command window, and select the stereo_masking test and the test can be readily performed. To change the notch widths and the frequencies, the values for these can be manipulated in the top initial few lines of the first m-file.

Appendix II

The following feature matrix was used for the sequential information transfer analysis using the FIX programs.

	b	ch	d	dh	g	j	k	l	ll	m	n	nn	p	r	s	sh	th	t	v	y
voicing	y	n	y	y	y	y	n	y	y	y	y	y	n	y	n	n	n	n	y	y
place	bil	pal	pal	alv	vel	pal	vel	alv	pal	bil	alv	pal	bil	alv	alv	pal	alv	pal	labdent	pal
manner	sto	aff	sto	sto	sto	aff	sto	liq	liq	nas	nas	nas	sto	tri	fri	fri	sto	sto	app	app

Appendix 3

The following is one of the sample consonant confusion matrix from the AN/AD subject. The confusion matrices should be shaped in this format to do the information transfer analysis using FIX

```
b C D d g j k l L m n N p r s S T t v y
3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 0 0
0 0 0 0 0 0 0 3 3 0 0 0 0 0 0 0 2 0 0 0
0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0 2 3 0 0 0 0 0 0 0 2 0
0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0 0 0 1
0 0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 2
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

The following is a simple Matlab code to derive the confusion matrices in this format from closed set consonant identification data. The raw data should be arranged in the alphabetical order with respect to the stimuli in MS-Excel with the adjacent column containing the responses. Place the excel file in the Matlab path and write the name of the file in place of ‘noname’ throughout the code. After this, running the code will return to the consonant confusion matrices in a text format in the above shown manner

```
%%%%%%%%%%%%%%%%%

%%Code to derive the consonant confusion matrices from raw data in

%%excel format


[N,T,R] = xlsread('no name.xls ');

set = R;
stim = set(:,1);

resp = set(:,2);
matrix = confusionmat(resp,stim);

stimlist = stim(1:3:60);
srimlist = stimlist';

dlmwrite('no name.txt',stimlist','delimiter',' ');
dlmwrite('no name.txt',matrix,'-append','delimiter',' ');

clear all;clc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```