FREQUENCY DISCRIMINATION AND SPEECH IDENTIFICATION ABILITIES IN INDIVIDUALS WITH AND WITHOUT COCHLEAR DEAD REGIONS

Megha

Register No: 07AUD010

A dissertation submitted in part of fulfilment for the degree of

Master of Science (Audiology)

University of Mysore, Mysore

ALL INDIA INSTITUTE OF SPEECH AND HEARING,

MANASAGANGOTHRI, MYSORE- 570006

MAY 2009

To,

The Lord Almighty,

My Beloved Parents

And

Vinay Sir

CERTIFICATE

This is to certify that this Master's dissertation entitled "**Frequency discrimination and speech identification abilities in individuals with and without cochlear dead regions"** is a bonafide work in part of fulfillment for the degree of Master of Science (Audiology) of the student **Registration no: 07AUD010**. This has been carried 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.

Dr. Vijayalakshmi Basavaraj
Director
All India Institute of Speech & Hearing,
Manasagangothri, Mysore-570006

Mysore
May 2009

CERTIFICATE

This is to certify that this dissertation entitled **"Frequency discrimination and speech identification abilities in individuals with and without cochlear dead regions"** has been prepared under my supervision & 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.

Dr. Vinay S. N.
Guide
Lecturer in Audiology,
All India Institute of Speech & Hearing,
Mansagangothri, Mysore-570006

Mysore
May 2009

DECLARATION

This is to certify that this master's dissertation entitled **"Frequency discrimination and speech identification abilities in individuals with and without cochlear dead regions"** is the result of my own study and has not been submitted earlier to any other university for the award of any degree or diploma.

Mysore Registration no:

May 2009 07AUD010

Acknowledgement

The beginning of knowledge is the discovery of something we do not understand.

- Frank Herbert

I would like to extend my greatest gratitude to the lord almighty who has given me knowledge and carried me throughout my life at all parts of time, Thank you lord!!

I thank my Papa and Mamma for their constant love, care and support and being with me always.

My heartfelt thanks to my beloved guide, Vinay sir. Sir thanks for being there always, and for all the support throughout the dissertation. Thanks a lot sir……. And Congrats sir for guiding 1st dissertation……….

My sincere gratitude to Dr. S. R. Savithri for helping me in formulating my stimuli. Thanks for your support ma'm.

I would like to thank our beloved Director Dr. Vijayalakshmi Basavaraj, for her support for successful completion of the dissertation, Thank you ma'm.

I thank Prof. Asha Yathiraj, HOD, Department of Audiology, for permitting me to use the instruments for my dissertation.

I take great privilege to thank Animesh sir and Sandeep sir who thought us so much in these 2 yrs and were directly or indirectly a part of this dissertation. It's a blessing to have such great teachers!!!

My gratitude also to Manjula ma'm and Rajalakshmi ma'm for imparting valuable knowledge to us, thank you….

Thanks to Devi ma'm, Mamata ma'm, Ramadevi ma'm, Revathi ma'm, and Dhanalakshmi ma'm for their support.

My gratitude to Dr. Nataraj , Director, J.S.S. Institute of speech and hearing, who laid a foundation for my speech and hearing career. Sir, my success today in this field is because of you, thank you sir.

A very special thanks to Sujit sir, for all the support and timely help and suggestions, thank you very much sir…

Special thanks to Sandhya ma'm for timely suggestions, thanks for being there…..

Thanks to my seniors, Asha, Dhanya, Hema, Sumitha, Sreeraj for being there.

My classmates….. Antony, Arun, Bhavya, Ismail, Gurdeep Singh, Manasa, Hmai, Meenakshi, Muthuselvi, Nikhil, Pooja, Ramesh, Sasmitha, Sharath, Sinthiya, Sruthy, Tamanna , Shuchi and Vivek and all my friends in Speech…… Thanks for being there always…..

Very special thanks to my batch mates, Bhavya, Arun, Anto, Gurdeep Singh, Shuchi, and Muthu for helping me in all directions.

Thanks to Dakshayini ma'm, Shivaprakash sir, and Librarian and all library staff for their support directly or indirectly.

Thanks to Vasantha Lakshmi ma'm for spending time patiently to do my stats…. Thank you ma'm…

A very very special thanks to my beloved friend and philosopher of my life….. Dr. Prakruthi…., who at all parts of my life held me when I was all fallen … thank you sweetie…

Last but not the least, my heartfelt thanks to all who participated in the study.

CONTENTS

CHAPTERS **PAGE NO**

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

CHAPTER 1

Introduction

Cochlear hearing loss has many causes and it is often seen that the damage is caused to the outer hair cells (OHCs) and inner hair cells (IHCs) in the cochlea (Moore, 2004a). The loss of IHCs leads to reduced efficiency of transduction, which results in elevated absolute thresholds and degraded transmission of information in the auditory nerve (Miller, Schilling, Franck & Young, 1997; Moore, 1998).

A dead region (DR) can be defined as a region in the cochlea where the IHCs and/or neurons are functioning very poorly, if at all present (Moore, 2001). DRs are relatively common among young and adult people with severe-to profound sensorineural hearing impairment (Moore et al., 2003; Preminger, Carpenter & Ziegler, 2005; Alexander, Cox, Rivera, Johnson & Gardino, 2007; Vinay & Moore, 2007; Aazh & Moore 2007a). DR is less common in people with absolute thresholds between 50 and 80 dB HL in at least two frequencies. The extent of a DR is defined in terms of its edge frequency (or frequencies), *fe,* which corresponds to the characteristic frequency (CF) of the IHCs and/or neurons immediately adjacent to the DR (Moore, Huss, Vickers, Glasberg, & Alcántara, 2000).

There are mainly two methods for determining the *fe.* Psychophysical tuning curves (PTCs) are one of the precise ways for determining the *fe* (Huss & Moore, 2003; Kluk & Moore, 2005; Moore & Alcántara, 2001; Sek, Alcántara, Kluk & Wicher, 2005). However, the disadvantage of PTCs is that it is lengthy and time consuming procedure. Though fast track methods of obtaining PTCs (Sek et al., 2005) have been developed, they are not available clinically.

One of the alternative and a quick method to determine the *fe* in DR is using Threshold equalizing noise (TEN) test developed by Moore et al. (2000). This utilizes threshold equalizing noise for obtaining the masked thresholds. The masked thresholds in TEN are usually measured only for the standard audiometric frequencies, which makes it a fast and an easy test to perform.

The presence of a DR can have several consequences for the perception of loudness, pitch and speech. Individuals with high-frequency DRs may experience a very rapid growth of loudness referred to as super-recruitment, with increasing sound level for signal frequencies falling well within a DR (McDermott, Lech, Kornblum, & Irvine, 1998). Huss and Moore (2005a) reported that tones falling more than half an octave into a DR usually do not evoke a clear pitch sensation and are often perceived with a pitch different (usually higher) than normal in individuals with both low- and high frequency DRs. The presence of DRs can also have a significant effect on the perception of speech and therefore has implications for the optimal setting of amplification through hearing aids and expectations about the likely benefit of a hearing aid.

Cochlear damages have been shown to induce changes in tonotopic maps in the central auditory system of animals. Neurons deprived from peripheral inputs start to respond to stimuli with frequencies close to the cut-off frequency or edge of the hearing loss, which then become over-represented at the neural level (Thai-Van et al., 2007). This neuronal arborization is mainly due to the effect of off-frequency listening, which a common phenomenon is observed in individuals with sensorineural hearing loss (Patterson & Moore, 1986).

Studies have examined whether discrimination abilities were enhanced near the hearing loss *fe* in patients with hearing loss of cochlear origin (Buss, Hall, Grose, & Hatch, 1998; Mc Dermott et al., 1998; Thai-Van, Micheyl, Norena, & Collet, 2002). The latter two studies revealed that the difference limens for frequency (DLFs) were found to be significantly enhanced at or near the *fe* in patients with steeply sloping, high-frequency hearing loss, estimated using the TEN (SPL) test.

Thai-Van, Micheyl, Moore, and Collet (2003) suggested that local improvement in difference limen frequency (DLFs) represents a side effect of neurophysiological mechanisms that have no major perceptual consequences on speech or music perception. However, studies of the intelligibility of low-pass filtered speech for individuals with DRs suggest that this may not be true. Under some filtering conditions individuals with DRs obtain better scores than individuals without DRs (Vestergaard, 2003; Vickers, Baer, Fullgrabe, Vinay, & Moore, 2006). Hence there are equivocal studies regarding effect of filtering on speech perception in individuals with and without DRs. Studies need to be carried out systematically in order to ascertain the results obtained. The present study considered the variables affecting speech perception ability in which, frequency information is carried more. Thus, the present study was undertaken to study the DLF enhancement in individuals with and without DRs across the frequencies (1 kHz, 2 kHz & 4 kHz) and to study the effect of DLF enhancement on speech identification scores.

Need for the study

The relationship between frequency discrimination abilities and speech identification abilities are not similar in individuals with DR and those without DR. This is proven by the various consequences of DR, like altered perception of loudness, pitch and speech which is different from that of an individual with sensorineural hearing loss without DR. Thus, these phenomenon need to be studied, as these have implications in fitting the amplification devices for individuals with DR.

- The enhancement of the frequency discrimination at the *fe* has been proven by various authors earlier (Thai-Van et al., 2003; Vickers et al., 2006; Kluk & Moore, 2006; Moore & Vinay, 2009). However, frequency discrimination at various *fe*'s has not been studied. Studying frequency discrimination across *fe*'s will help us to understand the extent of frequency discrimination enhancement at different *fe*'s.

- Speech perception involves a wide range of frequencies and speech perception is dependent on the degree of frequency discrimination abilities. This is proved by the fact that individuals with poor frequency discrimination abilities exhibit poor speech recognition scores as evident in cochlear hearing loss individuals (Moore, 1998). A correlation study on speech perception abilities and PTCs in hearing impaired listeners revealed that the speech perception performance with broadband noise correlated with the bandwidth of the PTC and performance on low pass noise correlated with the changes in the low frequency changes in the

PTC indicating speech perception bandwidth (Stelmachowicz, Jesteadt, Gorga, & Mott, 1985).

Thai-Van et al. (2003) suggested that local improvement in DLFs represents a side effect of neurophysiological mechanisms and have no major perceptual consequences on speech or music perception. However, studies of the intelligibility of low-pass filtered speech for individuals with DRs suggest that this may not be true. But, it is also seen that the different filtering conditions enhanced the speech perception scores in individuals with DRs (Vestergaard, 2003; Vickers et al., 2006). Thus there is a need to investigate this phenomenon.

- Also, the enhancement of DLF at/ near *fe* for individuals with cochlear dead region across different *fe* and in turn which may enhance the speech perception abilities of speech stimulus which are filtered till the different *fe*, have not been studied.

If, for individuals with DRs, a larger than normal region of the auditory cortex is devoted to the analysis of frequencies just below *fe*, (Robertson & Irvine, 1989; Rajan, Irvine, Wise, & Heil, 1993; Schwaber, Garraghty, & Kaas, 1993), then it is possible that this auditory cortex reorganization makes individuals with DRs more effective at extracting useful information from lower frequencies in the speech (Vickers et al., 2006). Kluk (2005) and Thai-Van et al., (2003) have suggested that a way of testing this hypothesis would be to assess whether the magnitude of the DLF enhancement was related to the efficiency in using low-frequency speech information.

Objectives of the study

The objectives of the study are:

1. To assess the frequency discrimination abilities in individuals without and with cochlear dead regions at 1 kHz, 2 kHz and 4 kHz edge frequencies.

2. To assess the speech identification abilities in individuals without and with cochlear dead region at 1 kHz, 2 kHz and 4 kHz edge frequencies.

3. To assess the correlation between the frequency discrimination abilities and speech identification abilities in individuals without and with cochlear dead regions at 1 kHz, 2 kHz and 4 kHz edge frequencies.

CHAPTER 2

REVIEW OF LITERATURE

CHAPTER 2

Review of literature

2.1 Overview

Cochlear hearing loss is often associated with damage to the hair cells within the cochlea. This damage to the cochlea can give rise to hearing loss in two main ways. Firstly, damage to the outer hair cells (OHCs) impairs the active mechanism in the cochlea, which results in the basilar membrane (BM) response to low-level sounds which are smaller than normal (Ruggero, 1992; Yates, 1995; Moore, 1998). Hence, the input sound level must be increased to give a just-detectable amount of vibration on the basilar membrane. Secondly, inner hair cells (IHCs) damage can result in reduced efficiency of transduction, so a greater than normal amount of BM vibration is necessary to reach the absolute threshold. Sometimes, the IHCs at certain places along the BM may be completely non-functioning or even missing. In addition, the neurons innervating those regions may be non-functioning or degenerated. Such places as referred to as “dead regions” (DRs) (Moore and Glasberg, 1997).

2.2. Concept of Cochlear Dead Region

A dead region can be defined as a region in the cochlea where the IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected (if it is sufficiently intense) by off-place or off-frequency listening (Moore, 2004).

In a region of the cochlea where either the IHCs or neurons are completely non-functional, there is no transduction of BM vibration into action potentials in the auditory nerve; thus, no information about BM vibration in that region is transmitted to the brain. However, a tone with a frequency falling into a dead region (DR) may be detected via upward or downward spread of excitation to region where there are functioning IHCs and neurons, i.e., such a tone may be detected at a region where the amount of BM vibration is lower than at the CF region, but the IHCs and neurons are functioning more effectively (Florentine & Houtsma, 1983; Moore, 1998, 2001, 2004a; Thornton & Abbas, 1980; Turner, Burns & Nelson, 1983; Moore & Alcántara, 2001).

2.3 Prevalence of dead regions

DRs are relatively common among young and adult people with severe-to profound sensorineural hearing impairment. Moore et al. (2003) reported that 69.7 % of the 33 tested teenagers with severe-to-profound hearing loss met the criteria for a DR at medium to high frequencies in at least one ear.

Preminger et al. (2005) reported a prevalence of 16.5 % of high frequency DRs and 12.5% of low or mid frequency DRs in a population of 49 adults with 50 - 80 dB sensorineural hearing loss. Alexander et al. (2007) assessed the prevalence of cochlear dead region among adult hearing impaired patients. Results revealed that prevalence was 33% subject-wise and 24% ear-wise had dead region and 35% males and 31% females had dead regions in one or both ears.

Aazh and Moore (2007a) administered TEN (HL) test using a test frequency 4 kHz only, for 98 ears with absolute thresholds between 65 and 95dB HL. 36 ears met the criteria for DR. The prevalence of DR exceeded 50% ,for hearing loss greater than 70 dB HL. However, the presence/ absence of DR could not be predicted reliably from the audiogram.

A recent study on Indian population by Vinay and Moore (2007a) estimated the prevalence of dead regions in 317 (592 ears) adult individuals with sensorineural hearing impairment as a function of audiometric threshold and frequency. Results showed that 177 (57.4%) individuals were found to have a dead region in one or both ears for at least one frequency. 54 women (54.5%) and 123 men (58.8%) had dead regions in one or both ears. 41.9% individuals had only a high frequency dead region, 2.3% individuals had only a low frequency dead region.

Thus, it can be seen that there is high rate of prevalence of DR among the sensorineural hearing loss population. The identification of an individual with DR becomes necessary as the rehabilitation process differs due to the abnormal consequences caused by the presence of DR.

2.4 Assessment of cochlear dead regions

A DR cannot be identified from the pure tone audiogram, although a potential indication of a DR may be given by the configuration of the hearing loss (Moore, 2001). The audiometric threshold can be misleading for the interpretation of DR by the configuration of hearing loss (Halpin et al., 1994; Moore, 2001; 2004a; Mackersie, Crocker & Davies, 2004; Kluk & Moore, 2006b). When the tone frequency falls close to the boundary of a DR, the audiogram may indicate only a moderate hearing loss, while the true hearing loss may be effectively infinite in this region. Thus, several researchers have used masking techniques to detect DRs and to define the value of edge frequency (*fe*) (Moore et al., 2000; Moore, 2001; Moore & Alcántara, 2001; Summers et al., 2003; Kluk & Moore, 2005).

2.4.1 Tests to identify cochlear dead regions

Two methods have been widely used to measure the edge frequency (*fe*). Both are based on the idea that, if the frequency of a signal (*fs*) falls into a DR, the signal is detected at a place where the amount of basilar membrane (BM) vibration is lower than at the peak, but the IHCs and neurons are functioning more effectively. One method involves measuring the masked threshold of a sinusoid in threshold-equalizing noise (TEN) and the other includes psychophysical tuning curves (PTCs) (Huss & Moore, 2003; Kluk & Moore, 2005).

2.4.1.a Psychophysical Tuning Curves (PTCs)

PTCs are the traditional psychophysical measures to assess the frequency selectivity on the basilar membrane. To measure Psychophysical tuning curves **(**PTCs), the sinusoidal signal is fixed in frequency and presented at a fixed (usually low) sensation level (about 10 dB SL). A narrowband noise is usually used as the masker. For each of several masker centre frequencies, the level of the masker required just to mask the signal is determined. For normally hearing individuals, the tip of the PTC (i.e., the frequency at which the masker level is lowest) always lies close to the signal frequency (Vogten, 1974; Moore, 1978). When plotted on a logarithmic frequency scale, PTCs usually have steep slopes adjacent to the tip, and a shallower low frequency tail.

For individuals with cochlear hearing loss, PTCs are usually broader, and sometimes lack the sharp tip (Hoekstra & Ritsma, 1977; Zwicker & Schorn, 1978; Moore & Glasberg, 1986) as shown in Figure 1.

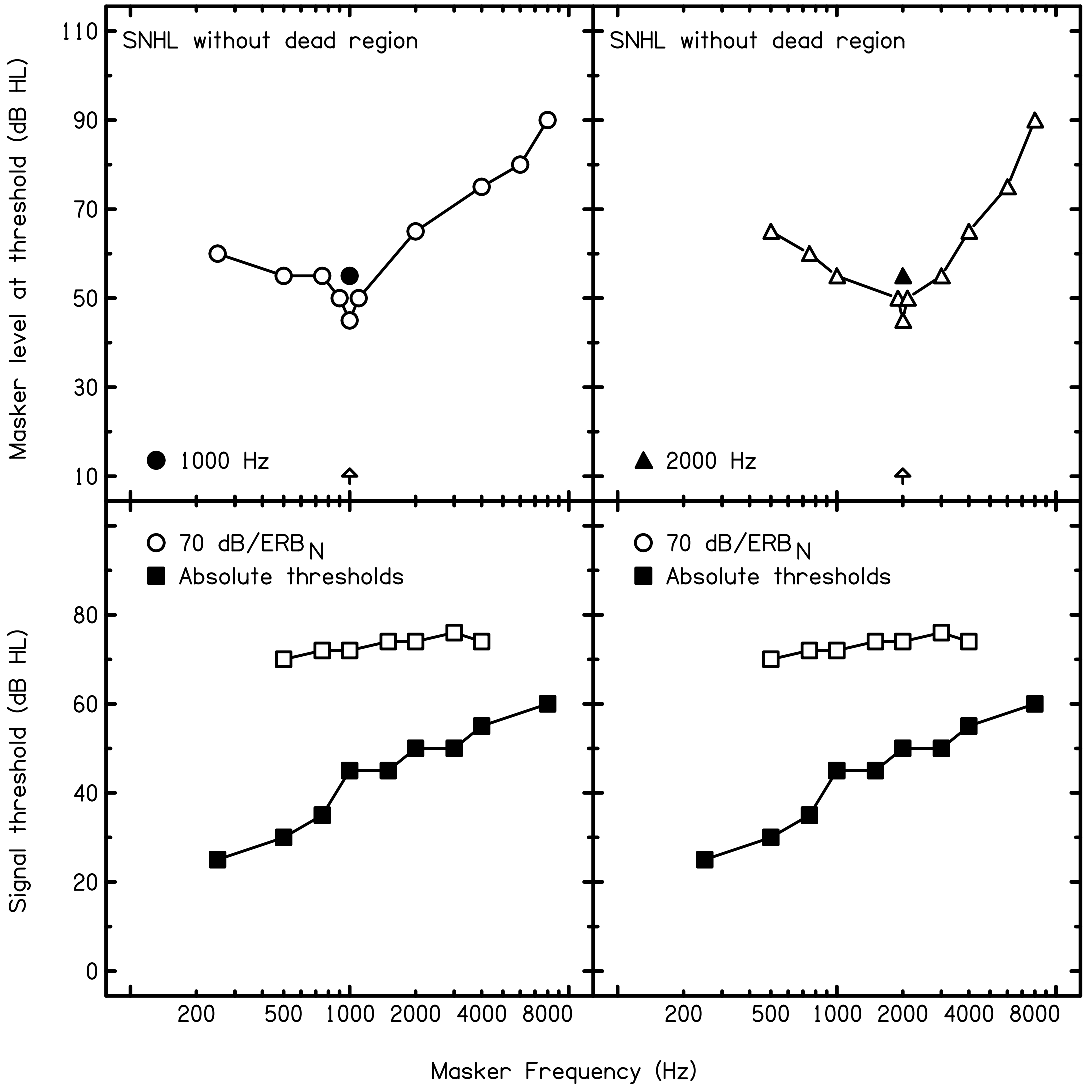

Figure 1. Psychophysical Tuning Curves in individuals with sensorineural hearing loss without dead region

For a PTC measured for an individual with hearing impairment with a dead region, and when the frequency of the signal falls within the dead region, the tip of the PTC was shifted away from the signal frequency. When the tip of the PTC is shifted downwards in frequency, this indicates a high frequency dead region beginning at the frequency of the shifted tip. The PTC for an individual with sensorineural hearing loss with DR is shown in Figure 2.

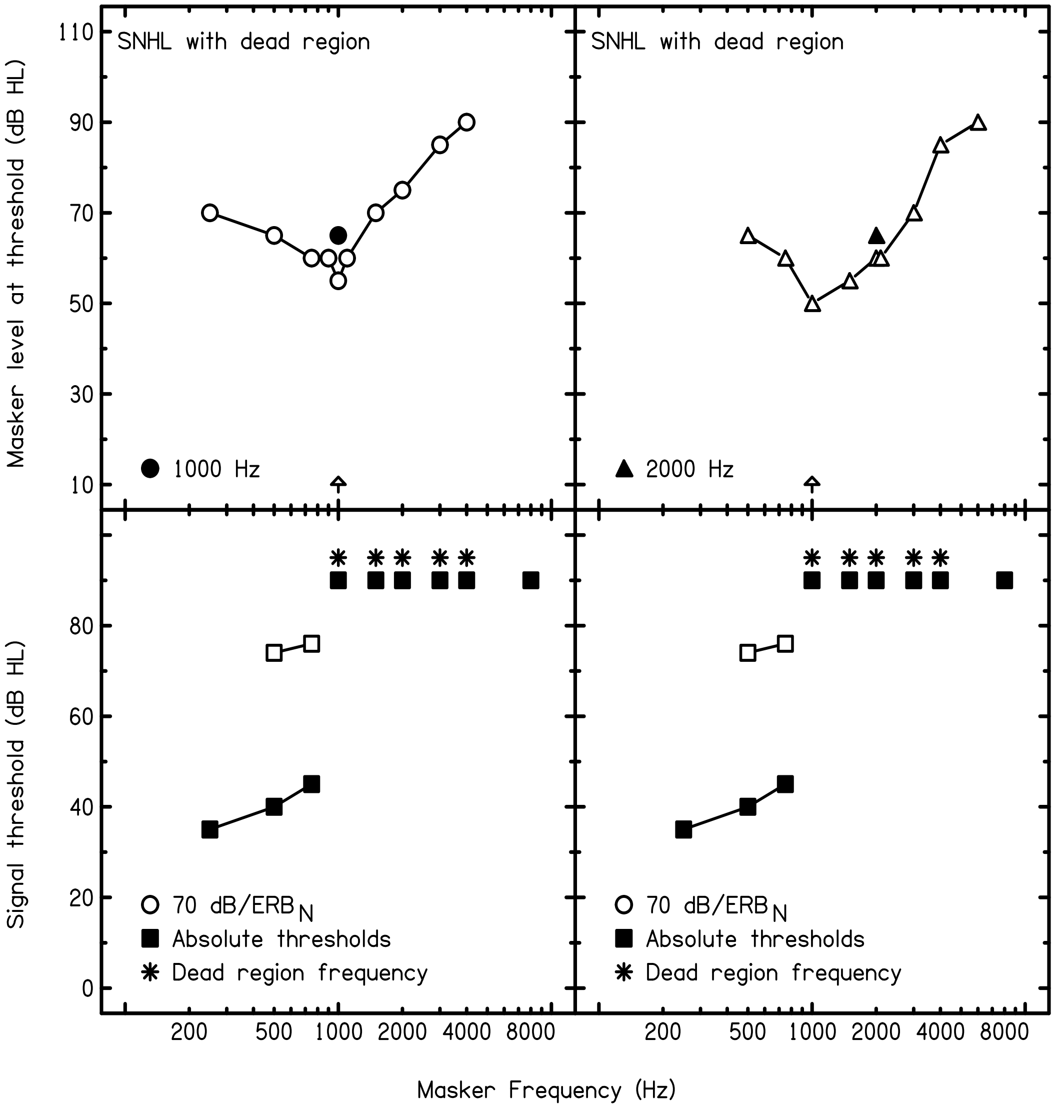

Figure 2. Psychophysical Tuning Curves in individuals with sensorineural hearing loss with dead region

The diagnosis of a dead region based on PTCs is time-consuming. To determine a PTC for a single signal frequency it is necessary to use at least five masker frequencies, and defining the frequency of a shifted tip may require many more masker frequencies (Kluk & Moore, 2004a). This typically takes at least 2 hours and longer. Thus, PTCs measured in the traditional way are not suitable for use in routine clinical practice.

In clinical use, PTCs are interpreted as reflecting frequency selectivity at the frequency/place where the signal is detected. However, the shapes of PTCs around their tips may be affected by a variety of factors which are not directly connected with the frequency selectivity. As PTCs derived in clinical settings are usually measured using simultaneous masking, there may be interactions between the signal and the masker. Consequence of this interaction is the generation of beats. The masked threshold may reflect the detection of these beats (Wegel & Lane, 1924; Ehmer, 1959a; Greenwood, 1971; Moore et al., 1998). Thus precautions must be taken to prevent detection of beats and combination tones when measuring PTCs.

2.4.1.b Threshold-equalizing noise (TEN) test

The threshold-equalizing noise (TEN) test involves measuring the threshold for detecting pure tones of various frequencies in a noise called Threshold-Equalizing Noise (TEN). The TEN is designed to produce equal masked thresholds over a wide frequency range for normally hearing listeners and for listeners with hearing impairment but without any DRs. TEN exists in two versions, called the TEN sound pressure level (SPL) and TEN hearing level (HL) tests.

In the first version of the test (Moore et al., 2000), the TEN (SPL) was designed to produce equal masked thresholds at all frequencies (from 0.25 kHz to 1 kHz) in dB SPL. In the more recent version of the test (Moore et al., 2004), the TEN (HL) was designed to produce equal masked thresholds at all frequencies (from 0.5 kHz to 4 kHz) in dB HL. The level of this noise is specified in terms of the level in a one-ERB_N wide band around 1 kHz (from 0.934 to 1.066 kHz), where ERB_N stands for the average value of the equivalent rectangular bandwidth of the auditory filter at moderate sound levels for young listeners with no known hearing defect (Glasberg & Moore, 1990).

The criteria for a DR are fulfilled if, for a given frequency, the masked threshold in the TEN is 10 dB or higher than the level per ERB_N of the TEN and the TEN produces at least 10 dB of masking (Moore, 2001; 2002, 2003, 2004a; Moore et al., 2000, 2001, 2004). For people with high-frequency (or low-frequency) DRs, the value of *fe* is usually taken as the lowest (or highest) frequency at which the masked threshold is at least 10 dB above the TEN level/ERB_N and at least 10 dB above the absolute threshold.

2.4.1.c. Correlation between Psychophysical Tuning Curves and Threshold Equalizing Noise test results

The consistency of the TEN and PTCs in identifying DRs has been examined over the years by many researchers. Some studies show a very good agreement between the results obtained using the two methods for adult listeners (Huss & Moore, 2003; Kluk & Moore, 2005; 2006a; Moore et al., 2000; 2004), while Summers et al., (2003) found only a 56 % agreement rate on the presence or absence of DRs at all tested frequencies, when using the TEN test and PTCs. This low agreement rate is likely to be due to problems with method of measurement and interpretation of the PTC results.

2.5 Consequences of cochlear hearing loss

The loss of sensitivity to weak sounds is one of the main causes of the problems experienced by people with cochlear hearing loss. Reduced frequency selectivity due to damaged outer and / inner hair cells alters the loudness perception, pitch perception and frequency discrimination abilities in individuals with cochlear hearing loss. The presence of a dead region worsens the perception of loudness, pitch and frequency discrimination abilities to a much greater extent. Tones with frequencies corresponding to a dead region are often described as sounding ‘noise-like’ or distorted (Huss and Moore, 2005a) as against a no dead region condition.

2.5.1 Loudness perception in cochlear hearing loss

The ability to detect changes in intensity, or to compare the intensity of two separate sounds, is usually assumed to be based on the loudness sensations evoked by the sounds. In people with cochlear hearing loss, a given change in intensity usually results in a larger than normal change in loudness. Hence the intensity discrimination would be better than normal hearing individuals.

The perception of loudness may be affected by at least four changes that occur with cochlear hearing loss (Moore, 1998).

1. Elevation in absolute threshold, which may be caused by loss of function of OHCs or IHCs, neural degeneration or a combination of all of these. Reduced functioning stria vascularis may also be involved.
2. A reduction in or loss of the compressive nonlinearity in the input–output function of the BM which is mainly associated with OHC dysfunction.
3. Loss of frequency selectivity which results in broader excitation patterns, which is again associated mainly with loss of OHC function.
4. Complete loss of IHCs or functional neurons at certain places within the cochlea (cochlear dead regions).

2.5.1.a Loudness perception in individuals without cochlear dead region

Loudness perception in individuals without cochlear dead region are comparable to normal at equal sound pressure levels (SPL) and are smaller (better) than normal hearing individuals at equal sensation levels (SL).

Florentine, Reed, Rabenowitz, Braede and Durlach (1993) studied the role of spread of excitation in intensity discrimination. They measured intensity discrimination for 1 kHz pulsed tones in hearing impaired individuals with various configurations of hearing loss. Individuals with increasing hearing loss above 1 kHz generally showed larger than normal difference limen intensity (DLI's) when compared at equal SPL and at equal loudness, but not when compared at equal SL. Individual with decreasing hearing loss above 1 kHz showed DLIs close to normal when compared at equal SPL and equal loudness, and showed smaller than normal DLIs when compared at equal SL. These results are consistent with the idea that information on the high frequency side of the excitation pattern is important for intensity discrimination.

Weber fractions (delta I/I) for gated 500-ms tones at 0.3, 0.5, 1, 2, and 3 kHz, and at levels of the standard ranging from absolute threshold to 97 dB SPL, were measured in quiet and in high-pass noise in five listeners with cochlear hearing loss and in three normal-hearing listeners by Schroder, Veimeister and Nelson (1994). In regions of hearing loss, the Weber fractions at a given SPL were sometimes normal. When the Weber fractions were normal or near normal, the addition of high-pass noise elevated the Weber fraction, strongly suggesting the use of spread of excitation at higher frequencies. Inversely, when the Weber fractions were elevated, the addition of high-pass noise produced no additional elevation of Weber fraction, suggesting an inability to use spread of excitation. When compared at the same SL, the Weber fraction was sometimes smaller in cochlear impaired than in normal hearing listeners. Thus, this shows the use of spread of excitation helps individuals with hearing loss to obtain better Weber fractions. This in turn suggests that intensity discrimination in cochlear hearing loss is smaller than normal hearing individuals.

2.5.1.b Loudness perception in individuals with cochlear dead regions

Loudness perception in individuals with cochlear DRs have been least studied. McDermott et al. (1998) revealed that individuals with high frequency hearing loss may experience a very rapid growth of loudness known as super-recruitment with increasing sound level for signal frequencies falling well within the region of hearing loss. He also suggested that loudness judgments might be influenced by the subjective quality of the tone falling in the region of hearing loss and individuals might associate the percept of distortion with a high loudness. It has been hypothesized that the super-recruitment may arise because of cortical re-organisation, leading to an over-representation of CFs just below the boundary of start of slope (Irvine and Rajan, 1995). Later review of this article by Moore (2001) have suggested that the kind of individuals McDermott et al. have tested fit to the criteria of dead regions. Thus, the results can be applicable to individuals with DRs.

In a recent study, Apoorva, Kruthika and Saranya (2009) studied the intensity discrimination in individuals with and without cochlear dead regions using the short increment sensitivity index (SISI). Results revealed that there was a significant difference in SISI scores between individuals with and without cochlear dead regions at equal SLs. They hypothesize that the possible reason for the increase in SISI scores in individuals with dead regions may be due to enhanced intensity discrimination due to cortical re-organization and over-representation in the auditory cortex for intensity in individuals with cochlear dead regions.

2.5.2 Pitch perception in cochlear hearing loss

Cochlear hearing loss results in a variety of changes in the way that sounds are represented in the auditory system. Four such changes are especially relevant for the perception of pitch.

1. Frequency Selectivity is Reduced: Auditory filters are broader than normal (Pick et al., 1977; Glasberg & Moore, 1986; Moore, 1998). Hence, the excitation pattern evoked by a sinusoid is also broader than normal.
2. The precision of phase locking can be reduced (Woolf et al., 1981; Miller et al., 1999); although this has not always been found. According to the temporal theory, reduced precision of phase locking should adversely affect frequency discrimination.
3. The propagation time of the traveling wave along the basilar membrane (BM) and the relative phase of the responses at different places may differ from normal because of loss of active mechanism, structural abnormalities or both (Ruggero, 1994; Ruggero, Rich, Robles & Recio, 1996). This could adversely affect mechanisms for pitch perception based on cross correlation of outputs of different points on the basilar membrane (Shamma & Klein 2000).
4. The presence of a dead region itself is a factor for altered perception of pitch.

2.5.2.a Pitch perception in individuals without cochlear dead region

Pitch perception in individuals without cochlear dead region have been studied since many years. Burns and Williamson (1981) studied the monaural pitch intensity functions in individuals with permanent cochlear hearing loss. Individuals with low frequency hearing loss (with normal high frequency thresholds) and high frequency hearing loss (above 1500 Hz) showed abnormally large pitch shifts with changes in intensity (up to 5% per bel) at low frequencies. Individuals with low frequency hearing loss and high frequency hearing loss (above about 4 kHz) showed essentially normal pitch intensity functions in regions where their thresholds were within normal limits. Thus, the study provided pitch perception patterns in individuals with both low frequency and high frequency hearing loss by studying the monaural pitch intensity functions.

Santurette and Dau (2007) it was observed that for the listeners with normal hearing, all types of binaural pitches were perceived. In hearing impaired listeners, some perceived all types of binaural pitches, but with decreased salience or musicality as compared to normal hearing listeners, some could only perceive the strongest pitch types and some were unable to perceive any binaural pitch at all. The performances of the hearing impaired listeners were not correlated with audibility. Reduced frequency selectivity was also found to impede the perception of binaural pitch stimuli. Thus, individuals with hearing impairment have difficulty perceiving pitch of a tone.

2.5.2.b Pitch perception in individuals with cochlear dead region

Many researchers reported pure tones sound highly distorted or noise-like to individuals with DRs (Huss & Moore, 2005a; 2005b). A study by Huss and Moore (2005) obtained pitch matches and octave matches for individuals with high frequency dead region. The dead region was estimated to start at about 1.2 kHz. Pitch matches within one ear (solely) was reasonably accurate for frequencies up to 1.25 kHz, and then become much more erratic, indicating that clear pitch percept was not obtained at frequencies above 1.25k Hz. For tones whose frequency fell well within the dead region, the perceived pitch was shifted upwards, although it was also unclear. Huss and Moore (2005a) reported that tones falling more than half an octave into a DR usually do not evoke a clear pitch sensation and are often perceived with a pitch different (usually higher) than normal in individuals with both low- and high frequency DRs. Huss and Moore (2005b) suggested that the noise-like perception was not necessarily associated with a DR, but often occurred when there was a substantial discrepancy between place and temporal information, i.e., when the signal frequency fell well within a DR. This discrepancy between place and temporal information may also affect the perception of pitch by individuals with DRs (Huss & Moore, 2005a; Moore, 2004a; Moore & Carlyon, 2005).

Thus in individuals with DRs,

- Pitch matches (of a tone with itself, within one ear) are often erratic, and frequency discrimination is poor, for tones with frequencies falling in a dead region. This indicates that such tones do not evoke a clear pitch sensation.
- Pitch matches across the ears of subject with asymmetric hearing loss, and octave matches within ears, indicate that tones falling within a dead region sometimes are perceived with a near normal pitch and sometimes are perceived with a pitch distinctly different from normal hearing individuals.
- The shifted pitches found for some individuals indicate that the pitch at low frequency tone is not represented solely by a temporal code. Possibly there needs to be a correspondence between place and temporal information for a normal pitch to be perceived (Evans, 1978).

These entire phenomenons indicate that the perception of pitch in individuals with DR is different from that of individuals without DR.

2.5.3 Frequency discrimination in individuals with cochlear hearing loss

People with cochlear hearing loss usually have auditory filters that are broader than normal. Hence, the excitation pattern evoked by a sinusoid is also broader than normal. According to the place theory, this should lead to impaired frequency discrimination. But according to the temporal theory, there should not necessarily be a relationship between frequency selectivity and frequency discrimination. However, frequency discrimination could be adversely affected by the reduced precision of phase locking that can occur in cases of cochlear damage. Frequency discrimination can be measured by either difference limens for frequency (DLFs) or frequency modulation detection limens (FMDLs). FMDLs were obtained in the present study as against frequency difference limes (FDLs), as FMDLs vary less with frequency (Moore & Skrodzka, 2002).

2.5.3.a Frequency discrimination in individuals without cochlear dead region

Frequency discrimination in individuals without cochlear dead region has been studied by many authors. Zurek and Formby (1981) measured FMDLs for ten individuals with sensorineural hearing loss using a 3 Hz modulation rate and frequencies between 0.125 kHz and 4 kHz. Their results indicated that the FMDLs tended to increase with increasing hearing loss at a given frequency. The worsening of performance was greater at low frequencies than at high frequencies.

Moore and Glasberg (1986c) measured FMDLs using a 4 Hz modulation rate at 80dBSPL in individuals with moderate unilateral and bilateral cochlear hearing loss.

The FMDLs were larger for the impaired ears than for the normal ears, by an average factor of 3.8 for 0.5 kHz and 1.5 Hz at 2 kHz. There was greater effect seen at lower frequencies than at higher frequencies.

Simon and Yund (1993) measured DLFs separately for each ear of individuals with bilateral cochlear damage and found that DLFs could be markedly different for the two ears at frequencies where absolute thresholds were the same. They also found that DLFs could be the same for the two ears when absolute thresholds were different. This indicated that there is no one to one correlation between the absolute threshold and the DLF.

In a more recent study by Moore and Skrodzka (2002) measured FMDLs for three young individuals with normal and four elderly individuals with cochlear hearing loss at modulation rates 2, 5, 10 and 20 Hz with and without the amplitude modulation (AM). Results indicated that hearing impaired individuals performed markedly poorer than the normal hearing individuals. There were similar scores seen across all the modulation rates. With the addition of AM the frequency discrimination scores were more disruptive and larger than those observed for normal hearing individuals. This study considers AM with the modulation rate of frequency, thus providing the interaction of AM with FM and also shows that hearing impaired individuals are not using the temporal cues effectively.

2.5.3.b Frequency discrimination in individuals with cochlear dead region

Frequency discrimination in individuals with DR have been a major focus of study by many researchers due to the fact that these individuals show a different pattern of results as against their no dead region counterparts. Way back, McDermott et al. (1998) found local improvements in frequency difference limens (DLFs) for frequencies near the cut-off frequency of a hearing loss, *fcut-off*, in individuals with high-frequency hearing loss, although no specific test for the presence of a DR was performed. Based on shape of the individuals' audiograms, it could be said that these individuals had a high-frequency DR (Moore, 2001).

By the pioneering work by McDermott et al. (1998), many studies have focused on to review the reasons for the DLF enhancement in individuals with DR. In the due time, studies using animals have shown that a DR can lead to re-organization of the tonotopic cortical map. This has been referred to as plasticity, i.e. the capacity of the system to make functionally appropriate adjustments in neural connection patterns (Rajan and Irvine, 1998b; Robertson and Irvine, 1989; Irvine et al., 1993; 2000; Salvi, Wang & Ding, 2000). There is a growing evidence of plasticity of the auditory system in adults with acquired hearing loss but without DRs (Ponton et al., 2001; Scheffler et al., 1998; Vasama & Makela, 1995) and in adults after fitting a hearing aid (Munro & Trotter, 2006; Philibert, Collet, Vesson & Veuillet, 2005; Robinson & Gatehouse, 1996). Auditory cortical neurons that are deprived of direct cochlear input due to a DR all become responsive to cochlear sites for which significant input is still present (remapping). These sites correspond to the place on the basilar membrane adjacent to the DR, i.e., to *fe*. In other words, there is cortical over-representation of *fe*.

Similar re-organization may occur in the human auditory cortex in people with DRs. Dietrich, Nieschalk, Stoll, Rajan and Pantev (2001) using magnetoencephalographic (MEG) measurements examined the responses of the auditory cortex in people with high-frequency cochlear hearing loss. They observed an increase in the value of the dipole moment for frequencies near the cut-off frequency of a hearing loss (defined as the frequency adjacent to the sharp deterioration in threshold at high frequencies, *fcut-off*), compared to frequencies away from *fcut-off* (the dipole moment indicates the total strength of cortical activation, i.e., the number of neurons active during a cortical response. If this number increases, the dipole moment also increases). Thus, Dietrich et al. (2001) showed expansion of the cortical representation of *fcut-off*.

In humans, the presence of a DR might lead to an expansion in the representation of frequencies near *fe* in the auditory cortex and therefore to better frequency discrimination for these frequencies. Rajan and Irvine (1998b) suggested that, for injury-induced auditory cortex reorganization to occur there must be a cochlear region in which damage is so comprehensive that there is no neural outflow from this region, i.e. there should be a DR.

Several researchers attempted to investigate the relationship between the cortical re-organization revealed by better frequency discrimination performance and the presence or absence of DRs. Thai-Van et al. (2002) measured frequency difference limens (DLFs) in 20 individuals with high-frequency hearing loss. At least 12 frequencies were tested at intervals of 1/8 octave over a range of 1.5 octaves around the cut-off frequency for hearing loss (*fe*). Results showed that DLFs were significantly smaller in a frequency band 1/4 octave wide centered on *fe* than in the other bands. A local improvement in DLF around *fe* was observed in the steep- and medium-slope groups and was confirmed statistically in the steep-slope group. Similar measurements in individuals with low-frequency or notched hearing loss allowed the authors to establish the presence of similar local improvements in DLFs around audiogram edges. These results, which suggest the slope of the hearing loss to be the most important factor for the occurrence of local DLF improvements, are consistent with both an interpretation in terms of peripheral mechanisms and one in terms of central mechanisms, i.e. injury-induced neural reorganization.

Thai-Van et al. (2003) conducted a similar experiment to that of McDermott et al. (1998), but they measured DLFs for stimuli roved over a 12-dB range to prevent use of loudness cues and they also diagnosed individuals as having DRs using the TEN(SPL) test (Moore et al., 2000). Thai- Van et al. (2003) reported enhanced DLFs at frequencies consistently lower than the value of *fe*. This is postulated that this discrepancy between the value of *fe* and the frequency for which the enhanced DLF was observed was due to errors in determining the value of *fe*, as the TEN (SPL) test does not allow precise determination of the value of *fe*.

Similar study was done by Kluk and Moore (2006) who measured DLFs in individuals with DRs for whom the values of *fe* had been determined precisely using psychophysical tuning curves. DLFs were measured for thirteen individuals with a DR in at least one ear. Almost all individuals with bilateral hearing loss exhibited enhanced DLFs near *fe,* which is consistent with cortical reorganisation. This occurred for individuals whose audiograms had both steep and shallow slopes, regardless of hearing aid use, and for two individuals with low-frequency DRs.

Thus, all studies on frequency discrimination in individuals with DR support the fact that there is enhanced frequency discrimination at/ near the *fe*.

2.5.4 Speech perception in cochlear hearing loss

People with cochlear hearing loss frequently complain of difficulty in speech communication. The extent and nature of the difficulty depends partly on the severity of the hearing loss. Researchers suggest that the reasons for these difficulties in speech perception arise primarily because of the reduced audibility. Even if speech is amplified so that it is audible, the cochlear hearing loss person will still have problems in understanding speech.

Speech recognition deficits resulting from high frequency hearing loss may not be limited to the loss of high frequency speech information. The evidence shows that damage to basal region of the cochlea may be accompanied by physiological and behavioral changes such as reduced contributions from the tails of high frequency auditory nerve fibers (Kiang & Moxon, 1974); reduced phase locking and synchronization to low frequencies (Jorris et al., 1994); disproportionate loss of activity from low spontaneous rate afferent fibers (Schmiedt et al., 1996) and efferent fibers (Liberman et al., 1990)

2.5.4.a Speech perception in individuals without cochlear dead region

Individuals with sensorineural hearing loss (SNHL), particularly the elderly, tend to have the greatest amount of hearing loss in the higher speech frequencies (above 2 kHz), which generally corresponds to more extensive patho-physiological changes in the corresponding region of the inner ear (Liberman & Dodds, 1984; Willott, 1991). Thus, many authors have studied the effect of high frequency amplification on speech perception abilities in individuals with sloping high frequency hearing loss. However, the literature shows that there are equivocal studies for and against the high frequency amplification for sloping high frequency hearing loss. Most of the studies have used hearing aids to boost/ reduce high frequency information.

The optimum degree of high-frequency amplification is currently unclear. There are mixed results on this issue to date (Murray & Byrne, 1986; Sullivan et al., 1992). To the extent that deficits in speech recognition accompanying high frequency hearing loss are caused by a reduction in restorable high-frequency speech information, amplification should be beneficial. However, due to unique properties of the basal region of the cochlea, speech-recognition deficits from basal damage may extend beyond the loss of high frequency speech information. It has also been seen that damage to high frequency region may also impair speech recognition as a result of reduced phase-locking and synchronization to low frequencies or a disproportionate loss of activity from low-spontaneous rate afferent fibres and efferent fibres. By all these facts, it still remains unknown if providing high-frequency amplification would be beneficial for steeply sloping high frequency hearing loss. Indeed, recent studies (Ching et al., 1998; Hogan & Turner, 1998; Turner and Cummings, 1999) suggest that the provision of high-frequency amplification may result in a decrease in speech recognition for some listeners with severe high-frequency hearing loss.

Turner and Cummings (1999) evaluated the benefit of providing audible speech information to listeners with a high frequency hearing loss. Speech recognition was tested over a wide range of presentation levels for 10 listeners with various degrees and configurations of sensorineural hearing loss. Results showed that for listeners with a sloping loss, amplifying frequencies beyond 3 kHz resulted in little to no improvement in speech recognition scores when hearing loss exceeded 55 dB HL. For flat configurations, however, amplifying frequencies beyond 3 kHz resulted in an increase in speech recognition when hearing loss exceeded 55 dB HL. These results suggest that there is no benefit obtained from amplifying beyond 3 kHz for sloping hearing loss.

Hornsby and Ricketts (2003) compared the speech understanding of persons with flat hearing loss and sloping high frequency hearing loss with that of normal hearing controls to examine the contribution of speech information in various frequency regions. Speech understanding in noise was assessed using multiple low and high pass filter cut off frequencies for all groups of listeners. Results indicated that listeners with flat SNHL showed improvements comparable to those for listeners with normal hearing, as high frequency information was made available. Furthermore, although listeners with sloping SNHL made less use of high frequency information than with listeners with flat hearing loss, results suggested that high frequency speech information (>3 kHz) did improve speech understanding for listeners with sloping sensory neural hearing loss.

In a recent study by Amos & Humes (2007) examined contribution of audible high frequency information to speech understanding performance in listeners with varying degrees of high-frequency sensorineural hearing loss. 36 elderly hearing-impaired (EHI) and 24 young normal-hearing (YNH) listeners were tested in quiet [+20 dB speech-to-noise ratio (SNR)] and noise (+5 dB SNR) and under different band-pass conditions both without and with spectral shaping of the stimuli. Results revealed that for hearing impaired group spectrally shaped speech showed no change in performance between the mid-band and broadband conditions while the normal hearing group demonstrated improved speech understanding, which can be attributed to the higher frequencies for the broadband condition in both the unshaped and shaped conditions.

In summary, results of these studies suggest that restoring audibility of high frequency information to persons with high frequency SNHL provides limited benefit to speech understanding. However, there are studies which say that providing high frequency amplification in individuals with high frequency hearing loss has positive effects on speech intelligibility and understanding.

Schwartz et al. (1979) examined the effect of an experimental high-pass hearing instrument versus a conventional high frequency emphasis hearing instrument on word recognition and consonant discrimination in both quiet and noise conditions. Ten male listeners with bilaterally symmetrical high frequency sensorineural hearing loss past 1 kHz were tested in quiet and noise under 3 conditions: unaided, conventional high frequency emphasis hearing instrument (own aid) and wearing the experimental high-pass instrument. Results suggested similar benefit for both hearing instruments in the quiet conditions. However, in the noise conditions, results indicated a greater increase in recognition scores with the experimental high pass instrument. The experimental high-pass instrument’s frequency response amplified up to 5.2 kHz whereas most of the conventional high emphasis hearing instruments amplified up to 3 kHz – 4 kHz. The listeners reported that the high-pass hearing instrument was superior, quieter and improved clarity of speech.

Turner and Henry (2002) reported that listeners with sloping SNHL were able to use amplified high frequency speech information to improve speech understanding when listening in a background of noise regardless of the degree of hearing loss. Similarly, Turner and Brus (2001) evaluated the effects of providing audible speech information to the low and mid frequency regions for listeners with various degrees of sensorineural hearing loss. Nonsense syllable recognition was tested on 5 normal hearing and 13 hearing impaired listeners with a range of hearing loss in the low and mid frequency regions. Results showed that for frequencies below 2.8 kHz, amplification provided positive benefit for recognition scores regardless of degree of loss rather than the 55 dB HL. These results suggest that speech recognition scores will improve without amplifying beyond 3 kHz for listeners with any configurations.

Horwitz, Dubno and Ahlstrom (2002) found that people with high-frequency hearing loss often complain of difficulty understanding speech, particularly in noisy environments. This study was designed to determine if high-frequency hearing loss results in speech-understanding deficits beyond those accounted for by reduced high frequency speech information. Recognition of speech, both low-pass filtered and unfiltered, was measured for individuals with normal hearing and those with hearing loss limited to high frequencies. Nonsense syllables were presented in three levels of noise that was spectrally shaped to match the long-term spectrum of the speech. Scores for individuals with impaired high frequency hearing were significantly poorer than scores for individuals with normal hearing. In the case of the low-pass-filtered speech, performance differences between groups could not be attributed to differences in speech audibility, as high-frequency speech cues were absent for all individuals. These results are consistent with the hypothesis that high-frequency fibers encode useful low-frequency speech information.

Thus, results of these studies suggest that restoring audibility of high frequency information to persons with high-frequency SNHL provides more benefit to speech understanding.

2.5.4.b Speech perception in individuals with cochlear dead region

The presence of DRs can also have a significant effect on the perception of speech and therefore has implications for the optimal setting of amplification. Several researchers have examined the effect of various types of filtering and masking on the ability of people with DRs to understand speech (Vickers et al., 2001; Baer, Moore & Kluk, 2002; Vestergaard, 2003; Mackersie et al., 2004; Preminger et al., 2005).

Some of these studies suggest that, for people with high frequency DRs, there may be little or no benefit to speech discrimination from amplifying frequencies well inside a DR, i.e., more than an octave above *fe* (Vickers et al., 2001; Baer et al., 2002;

Vestergaard, 2003; Mackersie et al., 2004; Preminger et al., 2005). However, there still is some controversy concerning the right amplification recommendations.

Vickers, Moore and Baer (2001) examined the effect of high frequency amplification on speech perception for individuals with high-frequency hearing loss with and without dead regions. The speech stimuli were vowel–consonant–vowel (VCV) nonsense syllables, using one of three vowels /i/, /a/, and /u/ and 21 different consonants. The stimuli were subjected to the frequency-gain characteristic prescribed by the ‘‘Cambridge’’ formula, which is intended to give speech at 65 dB SPL the same overall loudness as for a normal listener, and to make the average loudness of the speech the same for each critical band over the frequency range important for speech intelligibility in a listener without a dead region. The stimuli for all other conditions were initially subjected to this same frequency-gain characteristic. Then, the speech was low-pass filtered with various cut-off frequencies.

For individuals without dead regions, performance generally improved progressively with increasing cut-off frequency. This indicates that they benefited from high-frequency information. For individuals with dead regions, two patterns of performance were observed. For most individuals, performance improved with increasing cut-off frequency until the cut-off frequency was somewhat above the estimated edge frequency of the dead region, but hardly changed with further increases. For a few individuals, performance initially improved with increasing cut-off frequency and then worsened with further increases, although the worsening was significant only for one individual. Thus, individuals with DR do not use high frequency information. They conclude that results have important implications for the fitting of hearing aids.

Similar to the study of Vickers et al. (2001); Bear et al. (2002) studied effect of high-frequency amplification on speech perception for individuals with high-frequency hearing loss with and without dead regions. In this study an additional background noise was given. The noise level was chosen separately for each subject to give a moderate reduction in intelligibility relative to listening in quiet. For individuals without dead regions, performance generally improved with increasing cut-off frequency up to 7.5 kHz, on average more so in noise than in quiet. For most individuals with dead regions, performance improved with cut-off frequency up to 1.5–2 times the edge frequency of the dead region, but hardly changed with further increases.

Vestergaard (2003) measured the intelligibility of speech low-pass filtered at several cut-off frequencies for individuals with high-frequency DRs with *fe* in the range 0.75 - 1.5 kHz, and with *fe* above 3 kHz. For speech that was low-pass filtered at 1 kHz, individuals with *fe* in the range 0.75 - 1.5 kHz performed, on average, 10 % better than individuals with *fe* above 3 kHz. This indicates that individuals with low values of *fe* were able to make more effective use of low-frequency speech information than individuals with high values of *fe*.

Mackersie et al. (2004) compared speech intelligibility for individuals with and without dead region diagnosed using TEN test. Speech identification scores were obtained for unfiltered condition and for low pass filtered condition at *fe*, 1.41*fe* and 2 *fe*. In quiet and in low levels of noise, scores were significantly higher for the unfiltered stimuli than for the filtered stimuli and performance was similar for both the groups. In high levels of noise, mean scores were higher for without dead region individuals, but the performance reached asymptote at a lower cutoff frequency for the ears with dead region. Overall results support that for individuals with extensive high frequency dead regions do not make an effective use of the speech information at high frequencies as individuals without dead regions.

In a recent study, Moore and Vinay (2009) studied frequency discrimination for low frequency sounds in individuals with and without acquired high frequency dead regions, as assessed using the TEN (HL) test as that of the present study. For the ears with dead regions, the value of *fe* was close to 1 kHz or 1.5 kHz. Three subjects with unilateral dead regions (with matched low-frequency audiometric thresholds across ears) were also tested. Three tasks were used: (i) frequency discrimination of sinusoidal tones. The level of every stimulus was roved over a 12-dB range to reduce the salience of loudness cues. The center frequencies used ranged from 0.5 kHz to just below *fe*; (ii) detection of sinusoidal amplitude modulation of a sinusoidal carrier. Carrier frequencies of 0.5 kHz and 0.8 kHz were used with all individuals, and an additional carrier frequency of 1.2 kHz was used for ears with *fe* close to 1.5 kHz and their matched counterparts. Modulation frequencies were 4, 50 and 100 Hz; (iii) identification of consonants in nonsense syllables. The syllables were low pass filtered at 1 kHz or 1.5 kHz (depending on the value of *fe*) and complementary high pass-filtered noise was presented to prevent use of information from neurons tuned above *fe*.

For the frequency discrimination task, the ears with dead regions showed a significant local improvement (enhanced thresholds) for frequencies just below *fe*, as has been reported previously. For the individuals with unilateral dead regions, the enhancement occurred only for the ears with dead regions. Consonant identification was significantly better for the ears with than without dead regions, and this was true for the subjects with unilateral dead regions. They conclude that a dead region at high frequencies is associated with a better ability to process information at low frequencies. These effects may reflect cortical plasticity induced by the dead regions.

It is seen that high frequency DR individuals do not make much use of high frequency amplification. But this phenomenon is not limited only to high frequency DRs. Vinay and Moore (2007b) studied the speech recognition of high-pass filtered nonsense syllables was measured as a function of filter cutoff frequency for hearing-impaired people with and without low-frequency (apical) cochlear DRs. Results indicated that people with low-frequency DRs are able to make effective use of frequency components that fall in the range 0.57 *f(e)* to *f(e),* but that frequency components below 0.57 *f(e)* have deleterious effects. This also shows that individuals with DR, irrespective of region of loss (low or high frequency) will not be able to make use of the information provided to them which is inside the DR. Thus, high frequency amplification for high frequency DR is not beneficial for effective speech understanding.

2.5.5 Correlation between the frequency difference limen and speech perception in cochlear hearing loss

Speech perception difficulties for individuals with cochlear hearing loss is partly caused by the abnormalities in the perception of sounds that are above the threshold for detection and also might be because of poor frequency selectivity and poor frequency discrimination abilities. Several researchers have conducted correlational studies (Patterson et al., 1982; Tyler et al., 1982; Dreschler & Plomp, 1980, 1985; Glasberg & Moore, 1989; Van Rooji & Plomp, 1990; Lutman, 1991). Most studies have measured Speech recognition thresholds (SRTs) in noise and have assessed whether the SRTs can be accounted for the performance by various psychophysical tests. Most of the studies indicate that the suprathreshold abilities such as frequency selectivity (Horst, 1987) or temporal resolution can account for a significant proportion of variance in the SRTs.

2.5.5.a Correlation between the frequency difference limen and speech perception abilities in individuals without cochlear dead regions

There are studies which have shown that PTCs and speech scores with specific frequency content have correlated well in individuals with SNHL without DR. Preminger and Wiley (1985) measured PTCs for a 0.5 kHz signal and a 4 kHz signal in individuals with cochlear hearing loss of various configurations (high frequency, flat or low frequency). The test stimuli were consonant-vowel syllables which were categorized into three groups on the basis of predominant spectral energy as being high frequency, low frequency and diffuse. The individuals with high frequency loss had broader PTCs at 4 kHz, but normal at 0.5 kHz. These individuals achieved higher performance for low frequency consonants than for high frequency consonants. The individuals with flat hearing losses showed almost no frequency selectivity at 4 kHz and they performed poorly at identifying high frequency consonants. For individuals with low- frequency loss, the relation between PTC and consonant identification was not so clear.

Thibodeau and Van Tassell (1987) estimated frequency selectivity at 2 kHz by measuring the percentage- correct detection of a 2 kHz sinusoid as a function of the width of spectral notch in a noise, the notch being centered at 2 kHz. Two normally hearing individuals and seven SNHL individuals were taken. Discrimination of /di/ and /gi/ were also measured. There was a significant correlation between scores on the two tasks; individuals with poor frequency selectivity were also poorer at discriminating the syllables. Thus, indicating that there is one to one correlation for frequency selectivity and speech discrimination.

Dubno, Dirks and Ellison (1989) studied the contribution of certain frequency regions to consonant place perception for normal hearing listeners and listeners with high frequency hearing loss. Stop consonant recognition and error patterns were examined at various speech presentation levels and under low and high pass filtering. Differences in stop consonant recognition between normal hearing and hearing impaired listeners observed for low pass filtering at 2.8 kHz and for the unfiltered condition indicate that low pass filtering effects on normal hearing listeners stop consonant recognition are not comparable to the changes in recognition resulting from high frequency hearing loss. The effect of low pass filtering and threshold elevation, responses for the normal hearing listeners for low pass were found to be significantly different than responses in unfiltered condition for the hearing impaired. In other words, elimination of high frequency spectral energy by filtering was not equivalent to changes in recognition resulting from threshold elevation.

Hearing impaired listeners stop consonant recognition improved with addition of low frequency spectral region (0.35 kHz- 0.71 kHz), while normal hearing listeners performance was nearly optimal under the high pass at 710 Hz condition. The interpretation of this result is the contribution of the lower frequency spectral region may not be independent of the audibility of high frequency portions of the spectrum. For hearing impaired listeners, a wider audible bandwidth facilitates the discrimination of onset spectral shape that may be required for recognition of the stop consonants. This again proves that frequency information has high correlation with the speech recognition scores in individuals with SNHL without DR.

Ching, Dillion and Byrne (1997) attempted to determine the importance of psychophysical factors for speech recognition taking audibility into account. They presented speech in both quiet and noise under different filtering conditions. The deviations of the speech scores from the predicted values at high SLs were significantly correlated with a measure of frequency selectivity at 2 kHz.

Overall results support the fact that there is one to one correlation of frequency selectivity and speech performance in individuals without cochlear dead regions.

2.5.5.b Correlation between the frequency difference limen and speech perception in individuals with cochlear dead regions

There are little studies on correlation of frequency selectivity/ discrimination and speech perception abilities in individuals with cochlear DR. However, many studies on effect of low pass filtered speech on speech abilities in DR individuals have shown that performance is better with low pass filtered speech as against wide-band amplification (Vickers et al., 2001; Baer et al., 2002; Mackersie, et al., 2004).

Thai-Van et al. (2003) suggested that local improvement in DLFs “represents a side effect of neurophysiological mechanisms that have no major perceptual consequences on speech or music perception”. However, studies of the intelligibility of low-pass filtered speech for individuals with DRs suggest that this may not be the case; under some filtering conditions individuals with DRs obtain better scores than individuals without DRs.

Vickers et al. (2006) reported that individuals with high-frequency DRs could extract more information from low-pass filtered speech, than individuals without a DR. Individuals with *fe* at 0.75 kHz, obtained 42% correct when presented with speech low-pass filtered at 0.75 kHz and obtained 47% correct when the speech was low-pass filtered at 1.27 kHz (1.7*fe*). In contrast, individuals without any DR scored only 30% correct when presented with speech low-pass filtered at 0.75 kHz and 34% correct when the cut-off frequency was 1.27 kHz. This is consistent with the idea that, for individuals with DRs, a large region of the auditory cortex is devoted to the analysis of frequencies just below *fe*, as manifested by locally enhanced DLFs. It is possible that this auditory cortex reorganization makes individuals with DRs more effective at extracting information from lower frequencies in the speech.

Finally, Kluk (2005) concludes that the relationship between locally enhanced DLFs and the intelligibility of speech for individuals with DRs should be examined. If, for individuals with DRs, a larger than normal region of the auditory cortex is devoted to the analysis of frequencies just below *fe*, then it is possible that this auditory cortex reorganization makes individuals with DRs more effective at extracting “useful” information from lower frequencies in the speech. One way of testing this hypothesis would be to assess whether the magnitude of the DLF “enhancement” was related to the efficiency in using low-frequency speech information, or speech information in a narrow band around *fe*. The latter would be assessed by measuring the intelligibility of sharply-filtered sentences, and comparing results for individuals with and without DRs, but with similar amounts of hearing loss for frequencies close to *fe* (for the individuals with DRs).

CHAPTER 3

METHOD

CHAPTER 3

Method

The present study was conducted with an aim of studying frequency discrimination and speech identification abilities in individuals with and without dead regions. The study also aimed at correlating the frequency discrimination and speech identification abilities in individuals with and without dead regions.

Participant Selection Criteria

A total of 52 participants (82 ears) between the age group of 20 and 68 years with mean age of 43.6 years (SD =13.72) were taken for the study and they were divided into two groups based on the Threshold Equalization Noise (TEN) test results.

Group 1: Consisted of 38 ears with sensori-neural hearing loss without cochlear dead regions.

Group 2: Consisted of 44 ears with sensori-neural hearing loss with cochlear dead regions.

All the participants had acquired post-lingual sloping sensorineural hearing loss. Degree of hearing loss varied from minimal to moderate till the start of the slope / edge frequency in both Group 1 and Group 2 respectively. However, after the slope, the hearing thresholds were considered till 80 dB HL due to the limitations in administering TEN test above that threshold. Participants with air bone gap within 10 dB were selected for the study in both the groups. Participants with sharply sloping hearing loss i.e., 15-20 dB threshold increase per octave (Carhart, 1945) were taken in both the groups, with the slope starting from 1 kHz and above. For each ear with a dead region, a matching ear without a dead region was selected, either within the same participant or in a different participant. Participants in Group 2 with *fe* at 1 kHz, 2 kHz and 4 kHz were matched for the start of slope at corresponding frequency at 1 kHz, 2 kHz and 4 kHz. These frequencies, 1 kHz, 2 kHz and 4 kHz in Group 1 were named ‘A’, ‘B’ and ‘C’ respectively as the term edge frequency is inappropriate for individuals without dead regions. All the participants with speech identification scores greater than 60% were considered for the study.

Participants with no history or present complaints of middle ear disorders, neurological symptoms were selected for the study. All the participants were natïve speakers of Kannada with good language abilities.

Number of ears considered across each corresponding frequency at the start of slope / edge frequency for both Group1 and Group 2 respectively is shown in Table 1.

Table 1.

Number of ears considered in Group 1 and Group 2 across the corresponding frequencies at the start of the slope / edge frequencies

Frequency (kHz)	**Group 1**	**Group 2**
1/ A	12 ears	16 ears
2/ B	13 ears	14 ears
4/ C	13 ears	14 ears
Total	38 ears	44 ears

Instrumentation/ Material

Following instruments and materials were used for the study:

- Calibrated two channel diagnostic audiometer Orbiter 922 with TDH 39 headphones with MX 14AR cushion for performing the pure tone audiometry, speech audiometry, the TEN test and frequency discrimination test for both Group 1 and Group 2.
- Calibrated GSI Tympstar middle ear analyzer version 2.0 to rule out middle ear pathology.
- TEN (HL) test Compact Disc (CD), developed by Moore et al. (2004) to detect the presence or absence of cochlear dead region.
- Speech material was constructed based on the frequency composition of the Consonant- vowels (CVs). They were divided into low frequency, mid frequency and high frequency based on their frequency composition as per the classification given by Ramaswami (1999). A total of 30 CVs were used, 10 in each category.
- PRATT software version 4.5.16 to record and low pass filter the speech stimuli and Adobe Audition 1.0 to normalize the stimuli.
- Hewlett Packard (HP) laptop with 1.3 GHz Centrino Core 2 Duo processor connected to audiometer through auxiliary input for running the TEN (HL) test and presenting the unfiltered and low pass filtered speech stimuli.

All testing was done in a sound treated double room. The ambient noise levels were within permissible limits as recommended by ANSI (1999).

Procedure

Pure-tone thresholds were obtained at octave intervals from 0.25 kHz to 8 kHz and 0.25 kHz to 4 kHz for air conduction and bone conduction audiometry respectively, using modified Hughson-Westlake procedure developed by Carhart and Jerger (1959). Speech audiometry was done to obtain the speech recognition thresholds and speech identification scores. Immittance using the low frequency probe tone, 226 Hz, and acoustic reflex threshold measurements, both ipsilateral and contralateral thresholds were carried out to rule out the conductive component. The procedure was carried out in three phases.

Phase 1: Diagnosis of presence / absence of cochlear dead regions and to determine the edge frequency (fe)

TEN (HL) test was administered to diagnose cochlear dead regions in participants with sensorineural hearing loss and also to determine the edge frequency. The TEN (HL) level is specified as the level of a one-ERB_N wide band centered at 1 kHz, where ERB_N stands for Equivalent Rectangular Bandwidth of the auditory filter determined by using young normal hearing individuals at moderate sound levels (Glasberg & Moore, 1990; Moore, 2003). The TEN (HL) test was carried out as described by Moore et al. (2004), using a procedure similar to manual audiometry, except that masked thresholds were measured using a 2-dB step size. The TEN (HL) test was administered using a CD player run through a HP laptop, connected to an audiometer with TDH 39 earphones. Test frequencies were 0.5, 0.75, 1, 1.5, 2, 3, and 4 kHz. A TEN level of 70 dB HL/ERB_N was used for most individuals and a lower level of 50 dB HL/ERB_N was used for individuals with minimal and mild hearing loss, especially if they complained of loudness of the TEN.

A “no response (NR)” was recorded when the subject did not indicate hearing the signal at the maximum output level of the audiometer. The presence or absence of a dead region at a specific frequency was based on the criteria suggested by Moore et al. (2004).

- If the masked threshold in the TEN was 10 dB or more, above the TEN level/ERB_N, and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was interpreted to be present.
- If the masked threshold in the TEN was less than 10 dB above the TEN level/ERB_N, and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was interpreted to be absent.
- In cases where the TEN (HL) level could not be made high enough to elevate the absolute threshold by 10 dB or more i.e., the individuals with inconclusive results were not taken for the study as the edge frequency could not be determined in these individuals.

Phase 2: Establishing Frequency Modulation Difference Limen (FMDL)

Following the TEN test, frequency discrimination test for modulated signal was administered for both Group1 and Group 2 by obtaining the frequency modulation difference limens (FMDLs).

FMDLs were obtained using the two alternative forced choices. Two tones were presented successively, one modulated (0.2 %, 0.5%, 1.0%, 2.5%, 5.0%, 7.5%, 10.0%, 12.5% and 15.0 %) and other unmodulated tone. The level of presentation was 40 dB SL. The stimulus duration was 500ms. The participants were instructed to indicate whether the first tone or the second tone was modulated. The amount of modulation required for detection of the modulation was determined. Catch trials were presented at random to rule out the false responses.

FMDLs were obtained for individuals with dead regions and for individuals without dead regions at two frequencies. One frequency was selected at farther to the edge frequency/ corresponding slope, F_F, which can be defined as the nearest octave/ mid-octave frequency that is farther from the edge in DR / corresponding slope in individuals without DR. Another frequency was selected nearer to the edge frequency/ corresponding slope for without dead region individuals, F_N, which was *fe*- 1/8th octave, due to the fact that the enhancement is usually seen at this frequency and a farther frequency was taken to cross check this phenomenon. Table 2 depicts the edge / corresponding start of slope frequency and the corresponding frequencies at which the FMDLs were obtained.

Table 2.

Different frequencies at which frequency modulation difference limens were obtained for each edge frequency/ corresponding frequency at start of the slope

Edge Frequency / Corresponding slope (kHz)	**Frequencies tested**	
	F_F (kHz)	**F_N (kHz)**
1	0.5	0.8
2	1	1.8
4	3	3.8

Phase 3: Speech identification testing

Speech identification test was performed following the frequency discrimination testing. A combination of Consonant-Vowel (CV) stimuli were selected such that the CVs were concentrated in the low frequency, mid frequency and high frequency regions based on the classification given by Ramaswami (1999). Each CV was recorded by a male speaker in PRATT software, version 4.5.16. All the CVs were normalized to avoid the amplitude variations of the recorded speech stimuli using the Adobe Audition 1.0 software. A total of 30 CVs were taken and were divided into three lists based on their frequency composition. Table 3 shows the different list of CVs taken based on frequency composition of the same.

Table 3.

Speech Stimuli classified according to frequency composition

Low frequency stimuli	**Mid frequency stimuli**	**High frequency stimuli**
/bo/, /b^{h}o/, /hu/, /hu/, /mo/, /mu/, /po/, /pu/, /p^{h}u/, /p^{h}o/	/ka/, /k^{h}a/, /ga/, /g^{h}a/, /ţa/, /ţ^{h}a/, /da/, /d^{h}a/, /na/, /ha/	/ti/, /te/, /de/, /di/, /si/, /se/, /shi/, /ci/, /je/, /ňe/

The CVs constructed were presented without any filtering known as the unfiltered condition. Thus, there were three unfiltered lists, namely, unfiltered low frequency (ULF) , unfiltered mid frequency (UMF) and unfiltered high frequency (UHF). The CVs were low pass filtered (LPF) at different cut-off frequencies to produce the filtered low frequency (FLF), filtered mid frequency (FMF) and filtered high frequency (FHF) speech stimulus. The low pass filtering was done using the PRATT software version 4.5.16. The cut-off frequency of the low pass filtered speech was the edge frequency or the frequency at start of the slope for the three different frequencies (1 kHz, 2 kHz, and 4 kHz). Table 4 depicts the different speech lists presented to participants of both Group 1 and Group 2.

Table 4.

Speech lists and filtering conditions presented to Participants of Group 1 and Group 2 with respect to start of slope /Edge frequencies

Edge frequency/ Start of slope (kHz)	**Speech filtering condition**	**Low pass filtering cut off for filtered speech (kHz)**
1	ULF, UMF, FLF, FMF	1
2	UMF, UHF, FMF, FHF	2
4	UMF, UHF, FMF, FHF	4

The stimuli were randomized and the order of presentation of lists were also randomized and presented at 40 dB SL for most of the subjects or at the Most comfortable level (MCL) for higher degree of hearing loss, by connecting the CD player of the HP laptop to the audiometer. Written responses were obtained from all the participants.

Analysis of the obtained data was done using the Statistical Package for the Social Sciences (SPSS) version 16 software. The following statistical tests were applied to analyze the data obtained:

- Descriptive statistics was administered to obtain mean and standard deviation for age group, frequency discrimination difference limen scores, and speech identification scores in both Group 1 and Group 2.
- Two-way Analysis of Variance (ANOVA) was administered to:
    - To study effect of the dependent variables of corresponding start of slope / edge frequency, frequency discrimination and speech identification scores on independent variables of age and gender.
    - To study the dependent variable of frequency discrimination abilities within the individuals (Group 1 and Group 2) and across the independent variables of corresponding start of slope frequencies / edge frequencies.
- Duncan’s post hoc analysis was administered to study the pair-wise comparison of frequency discrimination abilities across the corresponding start of slope frequencies / edge frequencies.
- Paired sample t-tests were administered to study the comparison of:
    - Frequency discrimination abilities of farther frequencies (F_F) and nearer frequencies (F_N) within Group 1 across frequencies ‘A’, ‘B’ and ‘C’.
    - Frequency discrimination abilities of F_F and nearer frequencies F_N within Group 2 across edge frequencies 1 kHz, 2 kHz and 4 kHz.

- Mixed Analysis of Variance (ANOVA) was administered to study the effect of the dependent variables of low frequency, mid frequency and high frequency, unfiltered and filtered speech scores within and between the individuals (Group 1 and Group 2) and across the independent variables of corresponding frequencies ‘A’, ‘B’ and ‘C’ / edge frequency 1 kHz, 2 kHz and 4 kHz.
- Independent sample t-test was administered to study the pair-wise comparison of unfiltered and filtered speech identification scores for corresponding frequency ‘A’ / 1 kHz edge frequency between Group 1 and Group 2.
- Two- way ANOVA was administered to study:

  - The effect of dependent variable of speech identification scores for the corresponding frequency ‘B’ / edge 2 kHz on the independent variables of unfiltered and filtered conditions for both the Group 1 and Group 2.
  - The effect of dependent variable of speech identification scores for the corresponding frequency ‘C’ / edge 4 kHz on the independent variables of unfiltered and filtered conditions for both the Group 1 and Group 2.

- Paired sample t-tests were administered:

  - To study the comparison of speech identification scores of unfiltered and filtered conditions within Group 1 and Group 2 for frequencies ‘B’ and ‘C’/ edge frequencies 2 kHz and 4 kHz.

- Spearman’s correlation was administered to correlate the frequency discrimination abilities and speech identification scores for both Group 1 and Group 2.

CHAPTER 4

RESULTS AND DISCUSSION

Chapter 4

Results and Discussion

The results of the study are discussed under the following:

- Frequency discrimination abilities are discussed in terms of FMDL scores in individuals with cochlear dead regions (Group 2) and without cochlear dead regions (Group 1) at various edge frequencies / corresponding frequencies at the start of slope.

    - Frequency discrimination abilities in individuals with and without cochlear dead regions at various edge frequencies / corresponding frequencies at the start of slope for farther frequency (F_F).
    - Frequency discrimination abilities in individuals with and without cochlear dead regions at various edge frequencies / corresponding frequencies at the start of slope for farther frequency (F_N).
    - Comparison of the frequency discrimination abilities in individuals with and without cochlear dead regions at different edge frequencies / corresponding frequencies at the start of slope for farther frequency

- Speech identification abilities discussed in terms of speech identification scores in individuals with and without cochlear dead region at various edge frequencies / corresponding frequencies at the start of slope.

    - Speech identification scores of unfiltered low frequency (ULF) and filtered low frequency (FLF) for individuals with and without dead regions

- Speech identification scores of unfiltered mid frequency (UMF) and filtered mid frequency (FMF) for individuals with and without dead regions
- Speech identification scores of unfiltered high frequency (UHF) and filtered high frequency (FHF) for individuals with and without dead regions.
- Speech identification scores for frequency 'A' / 1 kHz edge frequency for Group 1 and Group 2.
- Speech identification scores for frequency 'B' / 2 kHz edge frequency for Group 1 and Group 2.
- Speech identification scores for frequency 'C' / and 4 kHz edge frequency for Group 1 and Group 2.

- Correlation of frequency discrimination scores with speech identification scores in Group 1 and Group 2.

4.1 Frequency discrimination abilities in individuals with and without cochlear dead regions

The results of frequency discrimination abilities for modulated tones have been discussed for farther frequency (F_F) and nearer frequency (F_N).

4.1.1 Frequency discrimination abilities in individuals with and without cochlear dead regions at various edge frequencies / corresponding frequencies at the start of slope for farther frequency (F_F)

The mean scores and standard deviation (SD) for FMDL scores of F_F for individuals with and without DR across the edge frequencies/ corresponding frequencies at the start of slope are shown in Table 5.

Table 5.

The mean and standard deviation (SD) for FMDL scores of F_F for individuals with and without dead regions across the edge frequencies/ corresponding frequencies at the start of slope

Participants	**Frequency (kHz)**	**N (ears)**	**Mean (%)**	**SD**
Without DR (Group 1)	1	12	3.20	1.95
	2	13	2.23	1.09
	4	13	1.38	0.79
With DR (Group 2)	1	16	1.84	0.76
	2	14	1.53	0.74
	4	14	1.42	0.85

**Note*. 1 kHz, 2 kHz and 4 kHz frequencies in Group 1 refers to ‘A’, ‘B’ and ‘C’ respectively.

In order to exclude the effect of independent variables of age and gender on frequency modulation difference limen (FMDL) for F_F across the edge frequency/ corresponding frequencies at the start of slope, two-way ANOVA was administered. Results showed that there was no effect of age and gender on F_F and in Group 1 as well as in Group 2 [F (1, 78) = 0.44, p>0.05].

Two-way ANOVA was administered to find the effect of frequencies at the start of slope / edge frequencies on the frequency discrimination abilities of F_F in Group 1 and Group 2.

Results of Two-way ANOVA revealed that there was statistically significant difference in FMDL scores of F_F between Group 1 and Group 2, [F (1, 76) = 7.78, p<0.05], and also across the corresponding frequencies at the start of slope /edge frequencies [F (2, 76) = 7.28, $p<0.05$]. However, there was no interaction observed between the Group 1 and Group 2 and the corresponding frequencies at the start of slope / edge frequency [F (2, 76) = 2.86, $p>0.05$].

Duncan’s post hoc analysis was administered to study if there was a statistically significant difference in FMDL scores of F_F between the various edge frequencies / corresponding frequencies at the start of slope. The results revealed that there was statistically significant difference between edge 1 kHz / corresponding frequency ‘A’ and edge 4 kHz / corresponding frequency ‘C’ but no statistically difference between edge frequency 1 kHz / corresponding frequency ‘A’ and edge 2 kHz / corresponding frequency ‘B’ and between edge 2 kHz / corresponding frequency ‘B’ and edge 4 kHz / corresponding frequency ‘C’. Figure 3 depicts the FMDL scores for Group 1 and Group 2 at 1 kHz and 4 kHz.

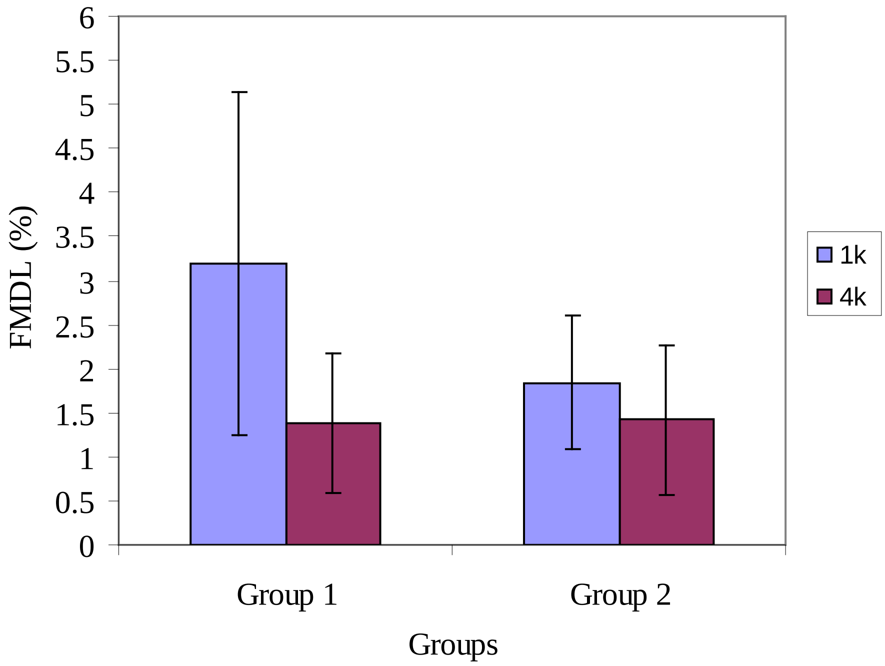

Figure 3. The FMDL scores at F_F for Group 1 and Group 2 at 1 kHz and 4 kHz

It can be seen from Figure 3 that overall mean FMDL scores for Group 2 were lower (Mean = 1.61) than Group 1 (Mean = 2.25), which shows that individuals with DR had better FMDLs than individuals without cochlear dead region. Across the edge frequency / corresponding frequencies at the start of slope for without DR, lower the edge frequency / corresponding frequencies at the start of slope, that is, 1 kHz edge / frequency ‘A’, individuals showed relatively worse FMDL scores than at 2 kHz and 4 kHz / ‘B’ and ‘C’ frequency. There was improvement in the FMDLs with increase in edge frequency / corresponding frequencies at the start of slope, for both the groups.

4.1.2 Frequency discrimination abilities in individuals with and without cochlear dead regions at various edge frequencies / corresponding frequencies at the start of slope for nearer frequency (F_N)

The mean scores and standard deviation (SD) for FMDL scores of F_N for individuals with and without DR across the edge frequencies / corresponding frequencies at the start of slope is shown in Table 6.

Table 6.

The mean and standard deviation (SD) for FMDL scores of F_N for individuals with and without DR across the edge frequencies / corresponding frequencies at the start of slope

Participants	**Frequency (kHz)**	**N (ears)**	**Mean (%)**	**SD**
Without DR (Group 1)	1	12	2.87	1.96
	2	13	2.23	1.09
	4	13	1.26	0.72
With DR (Group 2)	1	16	1.31	0.85
	2	14	1.17	0.74
	4	14	0.89	0.52

**Note.* 1 kHz, 2 kHz and 4 kHz frequencies in Group 1 refers to ‘A’, ‘B’ and ‘C’ respectively.

Two-way ANOVA was administered to exclude the effect of independent variables of age and gender on frequency modulation difference limen (FMDL) for F_N across the edge frequency/ corresponding frequencies at the start of slope. Results showed that there was no effect of age and gender on F_N and in Group 1 as well as in Group 2 [F(1, 78) = 0.49, p>0.05].

Two-way ANOVA was administered to find the effect of the frequency at the start of the slope/ edge frequency on frequency discrimination abilities of F_N in Group 1 and Group 2 across the corresponding frequencies at the start of slope / edge frequencies. Results revealed that there was statistically significant difference in F_N between Group 1 and Group 2, [F (1, 76) = 18.07, p<0.01], and also between the edge frequencies / corresponding frequencies at the start of slope [F (2, 76) = 6.33, p<0.05].

However, there was no interaction seen between the Group 1 and Group 2 and the edge frequency / corresponding frequencies at the start of slope [F (2, 76) = 2.15, p>0.05].

Duncan’s post hoc analysis was administered to study if there were statistically significant differences in FMDL scores of the F_N between the various edge frequencies / corresponding frequencies at the start of slope. The results revealed that there was significant difference in FMDL scores between edge 1 kHz / corresponding frequency ‘A’ and edge 4 kHz / corresponding frequency ‘C’ and edge 2 kHz / corresponding frequency ‘B’ and edge 4 kHz / corresponding frequency ‘C’. But there was no statistical difference between edge 1 kHz / corresponding frequency ‘A’ and edge 2 kHz / corresponding frequency ‘B’. Figure 4 depicts the FMDL scores at F_N for Group 1 and Group 2 at 1 kHz and 4 kHz and 2 kHz and 4 kHz.

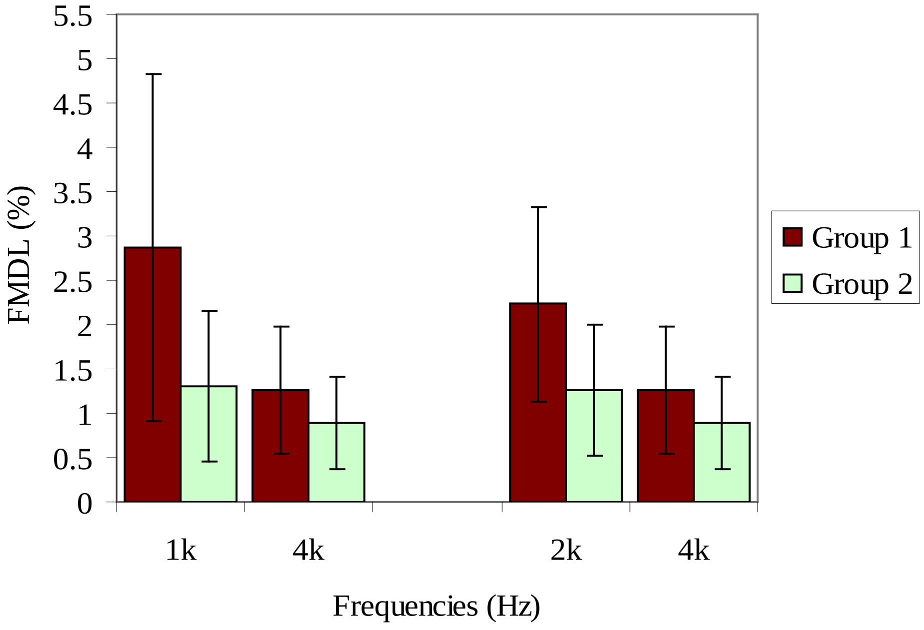

Figure 4. The FMDL scores at F_N for Group 1 and Group 2 at 1 kHz and 4 kHz and 2 kHz and 4 kHz

It can be seen from Figure 4 that the overall mean FMDL scores for Group 2 were lower (mean = 1.13) than Group 1 (mean = 2.10), which showed that individuals with DR had better FMDLs than individuals without cochlear dead region. Across the edge frequency / corresponding frequencies at the start of slope, lower the edge frequency / corresponding frequencies at the start of slope, that is, 1 kHz edge frequency / corresponding frequency ‘A’ individuals showed relatively worse FMDLs than 2 kHz and 4 kHz for both Group 1 and Group 2, which was similar to FMDL scores of F_F.

4.1.3 *Within groups comparison of frequency discrimination abilities in individuals with and without cochlear dead regions.*

Paired sample t-tests were administered to study the comparison of FMDL scores of F_F and F_N within Group 1 and the same was carried out within Group 2 at different frequencies at the start of slope / edge frequencies. Table 7 depicts the results of paired sample t-test results across edge frequencies / corresponding frequencies at the start of slope for FMDL scores of F_F and F_N for Group 1 and Group 2.

Table 7.

t value and significance across corresponding frequencies / edge frequencies at the start of slope for FMDL scores of F_F and F_N within Group 1 and within Group 2

Groups	**Frequency (kHz)**	**N**	**F_F**		**F_N**		**‘t’ value**	**Significance (2-tailed)**
			Mean (%)	**SD**	**Mean (%)**	**SD**		
Group 1	1	12	3.20	1.95	2.87	1.96	1.43	0.18
	2	13	2.23	1.09	2.23	1.09	------**	------**
	4	13	1.38	0.79	1.26	0.72	0.89	0.38
Group 2	1	16	1.84	0.76	1.13	0.85	2.57	0.02*
	2	14	1.53	0.74	1.17	0.74	1.43	0.17
	4	14	1.42	0.85	0.89	0.52	2.89	0.01*

*Note.** indicates significant difference at 0.05 level; **could not be compared as the mean values were equal.

Results of paired sample t-test indicated that there was no statistically significant difference between FMDL scores of F_F and F_N within Group 1 across the frequencies ‘A’, ‘B’ and ‘C’. However, there was statistically significant difference between FMDL scores of F_F and F_N within Group 2 at 1 kHz and 4 kHz edge frequencies, but no statistically significant difference between FMDL scores F_F and F_N at 2 kHz edge frequency. From the mean FMDL scores of F_F and F_N for Group 1 and Group 2, it was seen that the FMDL scores of F_F and F_N were almost similar in Group 1 whereas, in Group 2 the mean FMDL score of F_N was very much lower than the mean F_F values. This indicates that FMDLs were better/ enhanced near the edge frequency for individuals with cochlear dead region.

The results obtained in the present study were in support with the study by Kluk and Moore (2006), who studied difference limen for frequency (DLF) in individuals diagnosed to have cochlear dead regions at the higher frequencies. Results indicated that only a very small amount of local DLF enhancement at *fe*, which reflected the fact that the frequency at which DLF_{min} (that is the enhancement of DLF) occurred sometimes above and sometimes below *fe*. For most of the individuals, the DLF_{min} occurred at *fe* – $1/8^{th}$ octave frequency (Thai-Van et al. 2003; 2007). The DLFs for frequencies below and at *fe* showed good consistency across individuals. Thus in the present study, the FMDL at F_N frequency, which was one- eighth octave below *fe* for Group 2 showed better scores than F_F frequency, which was very much farther from the edge frequency. These findings were again consistent with the results of Thai-Van et al. (2003) who reported enhanced DLFs at or near *fcut-off*. However, the frequency at which the enhanced DLF was found was consistently lower than the value of *fe* estimated using the TEN (SPL) test. This may have occurred because the region of the cochlea that is over-represented may not be immediately adjacent to *fe*, but may lie at frequencies for which absolute thresholds are only slightly elevated. Such effects have been observed in animal studies (Irvine et al., 2001).

The interpretation of the DLF improvement in a narrow range around *fe* draws upon the neuro-physiological finding in animals (Irvine et al., 2001) which says that neighboring hearing-loss cut-off with a narrow frequency range is over-represented on the primary auditory cortex’s tonotopic map and thus more neurons are available for encoding frequencies falling in that range, and discrimination performance is correspondingly better. Thai-Van et al., (2002) have reported that if this interpretation is correct, the enhancement effect should increase as the *fe* gets lower, because lower the *fe*, larger is the cortical area that contains units having characteristic frequencies that are either above the edge. Thus, lower *fe* should be statistically associated with greater over-representation of the narrow edge frequency range and greater DLF enhancement. Conversely, in individuals with relatively high *fe*, improvements in frequency discrimination performance near the hearing-loss cut-off should be smaller. However, these predictions were not confirmed by the results of the present study.

In the present study, it was observed that the FMDL was worse at lower *fe* at 1 kHz compared to 2 kHz and 4 kHz. This was in contrast with the hypothesis of Thai-Van et al., (2002). It might be due to that at lower the *fe*, that is at 1 kHz, less number of low frequency fibres are available for taking over the cortical functions, as against 2 kHz and 4 kHz. Moreover, the hearing-loss slope is the predominant factor, that is, 1 kHz has steeper slope as compared to 2 kHz and 4 kHz, thus lowering the overall capabilities of individuals to perform the task.

Thus it was concluded that there was enhanced frequency discrimination abilities at *fe* – 1/8th octave frequency from the edge frequency, that is F_N for individuals with cochlear dead regions as against individuals without cochlear dead regions, which can be attributed to the cortical re-organization in cochlear dead region individuals.

4.2 Speech identification abilities in individuals with and without cochlear dead regions

Results of speech identification abilities for different filtering conditions have been discussed.

4.2.1 Speech identification scores of unfiltered low frequency (ULF) and filtered low frequency (FLF) for individuals with and without dead regions

The mean and standard deviation (SD) for speech identification scores of ULF and FLF for individuals with and without DR is shown in Table 8.

Table 8.

The mean and SD for speech identification scores of ULF and FLF for Group 1 and Group 2 for frequency 'A'/ edge frequency 1 kHz

Speech condition	**Groups**	**N**	**Mean**	**SD**
ULF	Group 1	12	3.75	1.05
	Group 2	16	2.62	1.20
FLF	Group 1	12	4.83	1.11
	Group 2	16	4.06	1.43

Mixed Analysis of variance (ANOVA) was administered to compare the unfiltered low frequency (ULF) speech identification scores and filtered low frequency (FLF) speech identification scores between Group 1 and Group 2.

The results revealed that there was a statistically significant difference between the speech identification scores of ULF and speech identification scores of FLF [F (1, 26) = 18.61, $p<0.001$] for both the Group1 and Group 2 at frequency ‘A’ / edge frequency 1 kHz. Results also indicated that there was statistically significant difference in the speech identification scores between the Group 1 and Group 2 [F (1, 26) = 6.65, $p<0.05$].

There was no interaction observed between the speech identification scores of ULF and FLF and Groups 1 and 2, which mean that both Group 1 and Group 2 followed the same pattern for the unfiltered and filtered condition [F (1,26) = 0.36, $p>0.05$].

4.2.2 Speech identification scores of unfiltered mid frequency (UMF) and filtered mid frequency (FMF) for individuals with and without dead regions

The mean and SD for speech identification scores for UMF and FMF for Group 1 and Group 2 across the corresponding frequencies ‘A’, ‘B’ and ‘C’ / edge frequency 1 kHz, 2 kHz and 4 kHz is depicted in Table 9.

Table 9.

Mean and SD for speech identification scores of UMF and FMF for Group 1 and Group 2 across the corresponding frequencies at the start of slope / edge frequency at 1 kHz, 2 kHz and 4 kHz

Speech condition	**Frequency (kHz)**	**Group 1**			**Group 2**		
		N	**Mean**	**SD**	**N**	**Mean**	**SD**
UMF	1	12	4.00	1.04	16	2.81	0.91
	2	13	5.30	1.03	14	4.92	1.07
	4	13	6.53	0.96	14	5.85	0.94
FMF	1	12	4.58	1.37	16	4.56	1.50
	2	13	5.53	0.77	14	6.85	1.02
	4	13	6.38	1.04	14	7.14	1.23

Mixed ANOVA was administered to study the effect of dependent variable of speech identification scores of unfiltered mid frequency (UMF) and filtered mid frequency (FMF) in Group 1 and Group 2 on the independent variable of across the corresponding frequencies at the start of slope / edge frequency at 1 kHz, 2 kHz and 4 kHz.

Results revealed that there was statistically significant difference in speech identification scores of UMF and FMF condition [F (1, 76) = 48.63, p<0.001]. There was statistically significant difference between the speech identification scores of UMF and FMF within the two groups [F (1, 76) = 28.48, p<0.001]. However there was no statistically significant interaction between the speech identification scores, edge frequencies/ corresponding frequencies at the start of slope and the two groups 1 and 2 ($p>0.05$).

Between the individuals, there was statistically significant difference in speech identification scores across the edge frequencies [$F (2, 76) = 52.18$, $p<0.001$]. However, there was no statistically significant difference in the speech identification scores between the two groups and there was no interaction seen between the two groups and the edge frequency ($p>0.05$).

Duncan's post hoc analysis revealed that all the three corresponding frequencies 'A', 'B' and 'C' / edge frequencies 1 kHz, 2 kHz and 4 kHz followed different trend in the speech identification scores, which shows that there was differences in the speech identification scores in individuals across the three edge frequency / corresponding frequencies at the start of the slope.

Two-way ANOVA was performed to study the effect of the speech identification scores of UMF between Group 1 and Group 2, across the three frequencies 1 kHz, 2 kHz and 4 kHz. Results revealed that there was statistically significant difference between Group1 and Group 2 [$F (1, 76) =11.55$, $p<0.01$] and also there was statistically significant difference across the different edge frequencies/ corresponding frequencies at the start of the slope [$F (2, 76) = 54.60$, $p<0.001$].

Duncan's post hoc analysis revealed that all the three corresponding frequencies 'A', 'B' and 'C', / edge frequencies 1 kHz, 2 kHz and 4 kHz, followed different trend in the speech identification scores of UMF. However, there was no significant effect of interaction between the two groups and the edge frequencies/

corresponding frequencies at the start of the slope on speech identification scores of UMF.

Two-way ANOVA was performed to study the effect of the speech identification scores of FMF between Group 1 and Group 2, across the three corresponding frequencies ‘A’, ‘B’ and ‘C’ / edge frequencies 1 kHz, 2 kHz and 4 kHz. Results revealed that there was statistically significant difference between Group1 and Group 2 [F (1, 76) = 6.68, $p<0.05$] and also there was statistically significant difference across the different edge frequencies/ corresponding frequencies at the start of the slope [F (2, 76) = 24.66, $p<0.001$]. Duncan’s post hoc analysis revealed that all the edge frequencies 1 kHz / corresponding frequency ‘A’ followed a different trend than 2 kHz / corresponding frequency ‘B’ and 4 kHz / corresponding frequency ‘C’ in the speech identification scores of FMF. However, there was no significant interaction between the two groups and the edge frequencies/ corresponding frequencies at the start of the slope on speech identification scores for FMF.

4.2.3 Speech identification scores of unfiltered high frequency (UHF) and filtered high frequency (FHF) for individuals with and without dead regions

The mean and SD for speech identification scores for UHF and FHF for Group 1 and Group 2 across the corresponding frequencies ‘B’ and ‘C’/ edge frequency at 2 kHz and 4k Hz is depicted in Table 10.

Table 10.

Mean and SD for the speech identification scores of UHF and FHF for Group 1 and Group 2

Speech condition	**Frequency (kHz)**	**Group 1**			**Group 2**		
		N	**Mean**	**SD**	**N**	**Mean**	**SD**
UHF	2	13	5.93	0.95	14	5.28	0.91
	4	13	6.84	0.98	14	6.00	0.78
FHF	2	13	5.46	0.77	14	7.78	0.80
	4	13	6.69	0.94	14	7.50	1.09

Mixed ANOVA was administered to study the effect of speech identification scores of UHF and FHF on the individuals with and without DR across the edge frequency 2 kHz and 4 kHz/ corresponding frequency 'B' and 'C'. Table 10 shows the mean and SD for the speech identification scores of UHF and FHF for Group 1 and Group 2.

Results revealed that there was statistically significant difference between the speech identification scores obtained between UHF and FHF [F (1, 50) = 34.52, p<0.001]. There was also statistically significant interaction between UHF and FHF and the two groups 1 and 2 [F (1, 50) = 64.19, p<0.001]. Also, there was statistical significant interaction between the speech identification scores of UHF and FHF and the two groups 1 and 2 and corresponding start of slope / edge frequency [F (1, 50) = 5.15, p<0.05]. However, there was no statistical significant interaction between speech identification scores of UHF and FHF with the edge frequencies 2 kHz and 4 kHz / corresponding frequencies ‘B’ and ‘C’ ($p>0.05$).

Between group effects revealed that there was statistically significant difference in speech identification scores between Group 1 and Group 2 [F (1, 50) = 4.13, $p<0.05$] and between frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz [F (1, 50) = 10.14, $p<0.01$]. There was also statistical significant difference between speech identification scores of UHF and FHF and the two groups 1 and 2 and frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz [F (1, 50) = 4.53, $p<0.05$].

Two-way ANOVA was administered to study the effect of speech identification scores of UHF in the participants Group 1 and Group 2 across the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz. Results revealed that there was statistically significant difference in speech identification scores of UHF in Group1 and Group 2 [F (1, 50) = 8.94, $p<0.01$] and also across the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz [F (1, 50) = 10.89, $p<0.01$]. However, there was no interaction effects seen between the two groups 1 and 2 and the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz ($p>0.05$).

Similarly, Two-way ANOVA was also performed to study the speech identification scores of FHF in the two groups and the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz. Results revealed that there was statistical significant difference in speech identification scores of FHF between the two groups 1 and 2 [F (1, 50) = 39.49, $p<0.001$] but there was no statistical significant difference between the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz ($p>0.05$). However, there was interaction effects seen between Group1 and Group2 and the frequency ‘B’ and ‘C’ / edge frequencies 2 kHz and 4 kHz [F (1, 50) = 9.25, $p<0.01$].

4.2.4 Comparison of speech identification scores in different filtering conditions across the edge frequencies/ corresponding frequencies at the start of slope

Results of Paired t- tests have been discussed for different speech filtering conditions across the edge frequency/ corresponding frequency at the start of slope for both group 1 and 2.

4.2.4.a Comparison of speech identification scores for different conditions at frequency ‘A’/ edge frequency 1 kHz for Group 1 and Group 2

Independent t- test was administered to compare the speech identification scores of ULF and FLF between Group1 and Group 2. Results showed that there was significant difference for speech identification scores of ULF [$t (26) = 2.57$, $p< 0.05$] between the two groups. But, that there was no significant difference for FLF speech identification scores ($p> 0.05$) between the two groups.

Paired sample t-test was performed to study the pair wise comparison of speech identification scores of ULF and FLF and UMF and FMF for both Group 1 and Group 2 for frequency ‘A’/ edge frequency 1 kHz . Table 11 shows the results of paired sample t-test for speech identification scores for speech identification scores of ULF and FLF and UMF and FMF for both the groups for edge frequency 1 kHz / frequency ‘A’.

Table 11.

t value and significance for frequency 'A'/ edge frequency 1 kHz for different filtering conditions for speech for both groups 1 and 2

	Group 1		Group 2	
Speech condition (Comparison Pair)	**t value**	**Significance**	**t value**	**Significance**
ULF- FLF	3.02	0.01*	3.36	0.00**
UMF- FMF	2.02	0.67	4.71	0.00**
ULF- UMF	0.71	0.49	0.58	0.56
FLF- FMF	0.89	0.38	1.93	0.07

Note. * indicates significance at 0.05; ** indicates at significance at 0.001 level.

Results of paired t-tests revealed that for Group 1, there was statistically significant difference between the speech identification scores of ULF and FLF [t (11) = 3.02, p<0.05] but there was no statistical significant difference between the speech identification scores of UMF and FMF. In Group 2, there was statistically significant difference between the speech identification scores ULF and FLF [t (15) = 3.36, p<0.001] and also between the speech identification scores of UMF and FMF [t (15) = 4.71, p<0.001]. This showed that both Group 1 and Group 2 individuals performed differently in unfiltered and filtered low frequency and mid frequency speech identification task. It was observed from the mean scores of Group 1 and Group 2 for the unfiltered and the filtered condition, the filtered condition resulted in better scores for both the groups.

Figure 5 and Figure 6 shows the mean raw speech identification scores for ULF and FLF and UMF and FMF respectively in Group 1 and Group 2 at corresponding frequency ‘A’/ edge frequency 1 kHz. It can be seen that the mean speech identification scores for the filtered conditions are better than the unfiltered speech identification scores. It can also been seen that the Group 1 performance is better than Group 2 at frequency ‘A’/ edge frequency 1 kHz.

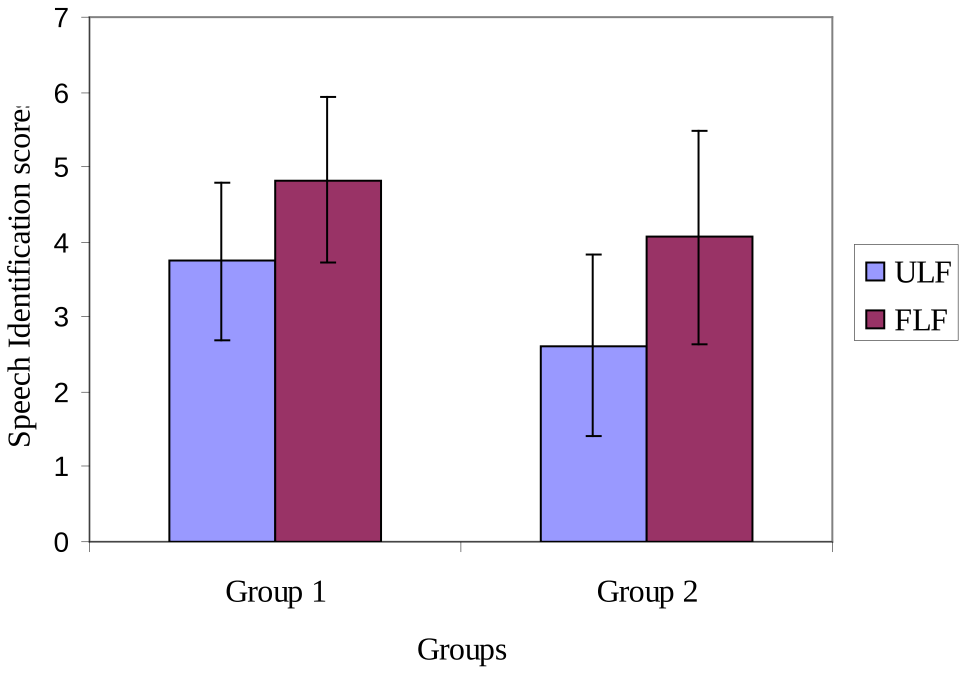

Figure 5. Mean raw speech identification scores for ULF and FLF in Group 1 and Group 2 at corresponding frequency ‘A’/ 1 kHz edge frequency

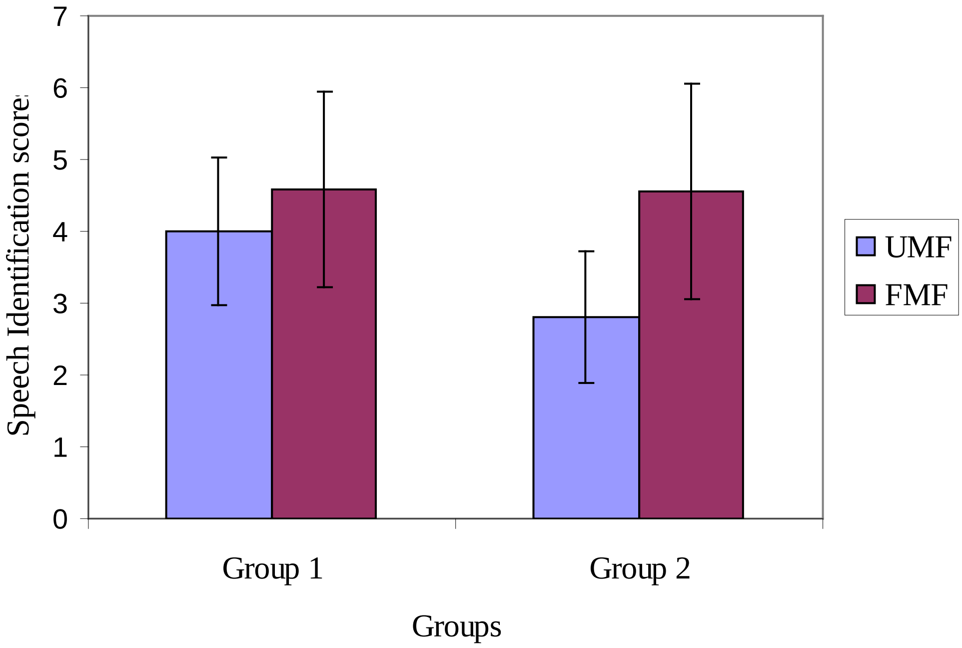

Figure 6. Mean raw speech identification scores for UMF and FMF in Group 1 and Group 2 at corresponding frequency ‘A’/ 1 kHz edge frequency

However there was no statistical significant difference between the speech identification scores of two unfiltered conditions of ULF and UMF and also between the speech identification scores of two filtered conditions of FLF and FMF in both group 1 and 2.

4.2.4.b Comparison of speech identification scores for different conditions at frequency ‘B’/ edge frequency 2 kHz for Group 1 and Group 2

Paired sample t-test was performed to assess the pair wise comparison of speech scores of UMF and FMF and UHF and FHF in frequency ‘B’/ edge frequency 2 kHz in both Group 1 and Group 2. Table 12 shows the results of paired sample t-test for speech identification scores in edge 2 kHz / corresponding frequency ‘B’.

Table 12.

t value and significance for frequency 'B'/ edge frequency 2 kHz for different filtering conditions for speech for both groups 1 and 2

	Group 1		**Group 2**	
Speech condition (Comparison Pair)	**t value**	**Significance**	**t value**	**Significance**
UMF- FMF	0.64	0.53	8.70	0.00**
UHF- FHF	2.52	0.27	12.31	0.00**
UMF- UHF	2.88	0.01*	1.58	0.13
FMF- FHF	0.22	0.82	4.19	0.00**

Note. ** Significant at 0.001 level; * significant at 0.05 level.

Results revealed that there was statistically significant difference between UMF and FMF and between UHF and FHF within the Group 2 [t (13) = 8.70, p<0.001] and [t (13) = 12.31, p<0.001] respectively. However, there was no statistical significant difference between the speech identification scores of UMF and FMF and between the speech identification scores of UHF and FHF within the Group 1 (p>0.05).

Figure 7 and 8 shows the mean raw speech identification scores for UMF and FMF and UHF and FHF respectively in Group 1 and Group 2 at corresponding frequency 'B' / edge frequency 2 kHz. It can be seen that the mean speech identification scores for Group 1 was almost similar for UMF and FMF and UHF and FHF. But in Group 2, the filtered speech condition was better than unfiltered speech condition. It can also been seen that the mean speech identification scores for FMF and FHF was better (higher) in Group 2 than Group 1. This indicates that individuals with cochlear dead region are performing better for filtered speech stimuli.

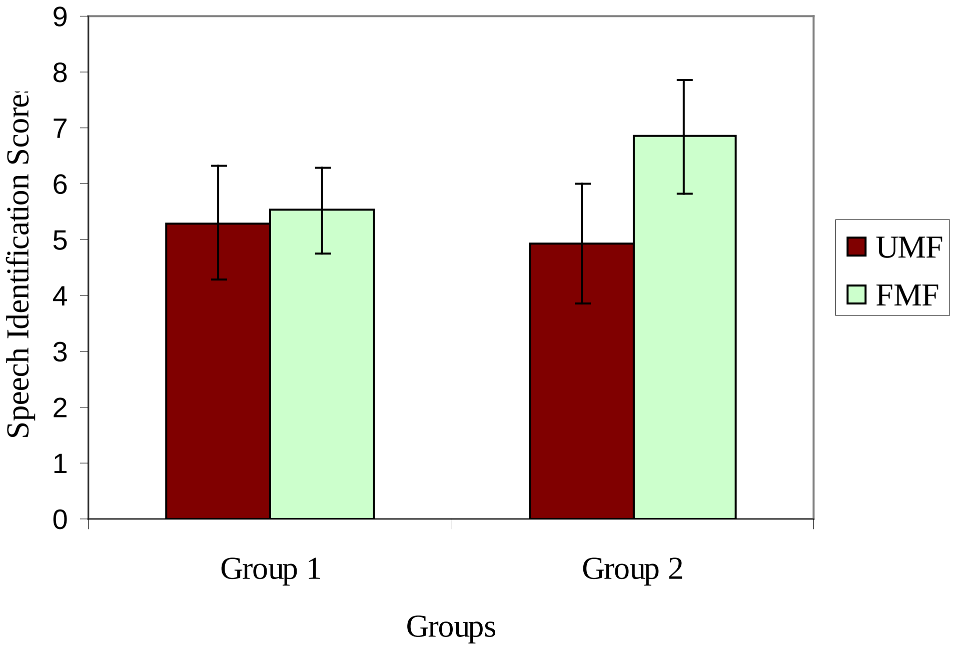

Figure 7. Mean raw speech identification scores for UMF and FMF in Group 1 and Group 2 at corresponding frequency ‘B’ / 2 kHz edge frequency

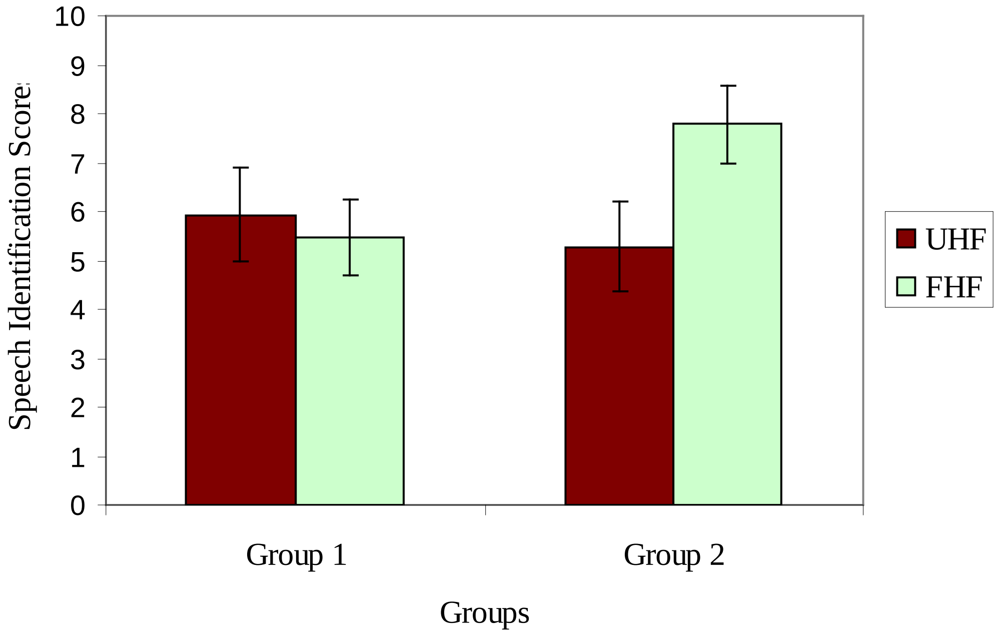

Figure 8. Mean raw speech identification scores for UHF and FHF in Group 1 and Group 2 at corresponding frequency 'B' / 2 kHz edge frequency

However there was statistical significant difference between the speech identification scores of two unfiltered conditions of UMF and UHF only in Group 1 and also between the speech identification scores of two filtered conditions of FMF and FHF in Group 2.

4.2.4.c Comparison of speech identification scores for different conditions at frequency 'C'/ edge frequency 4 kHz for Group 1 and Group 2

Paired sample t-test was performed to compare the speech identification scores of UMF and FMF and UHF and FHF in frequency 'C'/ edge frequency 4 kHz in both Group 1 and Group 2. Table 13 shows the results of paired sample t-test for speech identification scores in edge frequency 4 kHz / corresponding frequency 'C'.

Table 13

t value and significance for frequency 'C'/ edge frequency 4 kHz for different filtering conditions for speech for both groups 1 and 2

	Group 1		**Group 2**	
Speech condition (Comparison Pair)	**t value**	**Significance**	**t value**	**Significance**
UMF- FMF	0.41	0.68	4.22	0.001*
UHF- FHF	0.39	0.70	4.58	0.00*
UMF- UHF	1.76	0.10	0.69	0.50
FMF- FHF	1.07	0.30	1.32	0.20

**Note.* Significant at 0.01 level

Results revealed that there was statistically significant difference in speech identification scores between UMF and FMF and also between the speech identification scores of UHF and FHF within the Group 2 [t (13) = 4.22, $p<0.01$] and [t (13) = 4.58, $p<0.01$]. However, there was no significant difference between the speech identification scores of UMF and FMF and also between the speech identification scores of UHF and FHF within the Group 1 ($p>0.05$). There was also no statistical significant difference between the speech identification scores of two unfiltered conditions of UMF and UHF and also between the speech identification scores of two filtered conditions of FMF and FHF in both group 1 and 2.

Figure 9 and Figure 10 shows the mean raw speech identification scores for UMF and FMF and UHF and FHF respectively in Group 1 and Group 2 at 4 kHz edge frequency/ corresponding frequency 'C'. It can be seen that the mean speech identification scores for Group 1 was almost similar for UMF and FMF and UHF and FHF. But in Group 2, the filtered speech condition was better than unfiltered speech condition. It can also been seen that the mean speech identification scores for FMF and FHF was better (higher) in Group 2 than Group 1. This indicates that individuals with cochlear dead region are performing better for filtered speech stimuli.

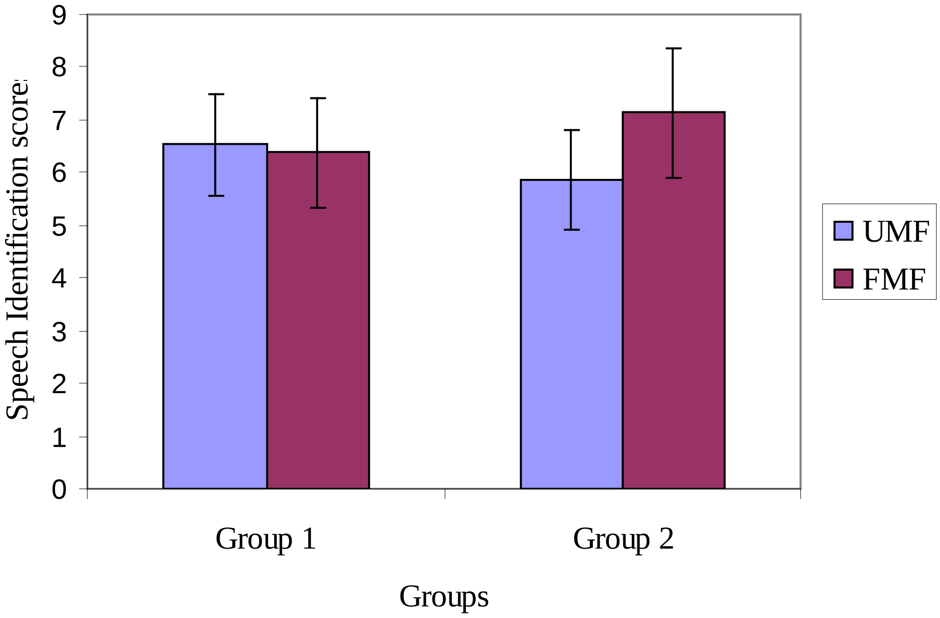

Figure 9. Mean raw speech identification scores for UMF and FMF in Group 1 and Group 2 at corresponding frequency ‘C’ / 4 kHz edge frequency

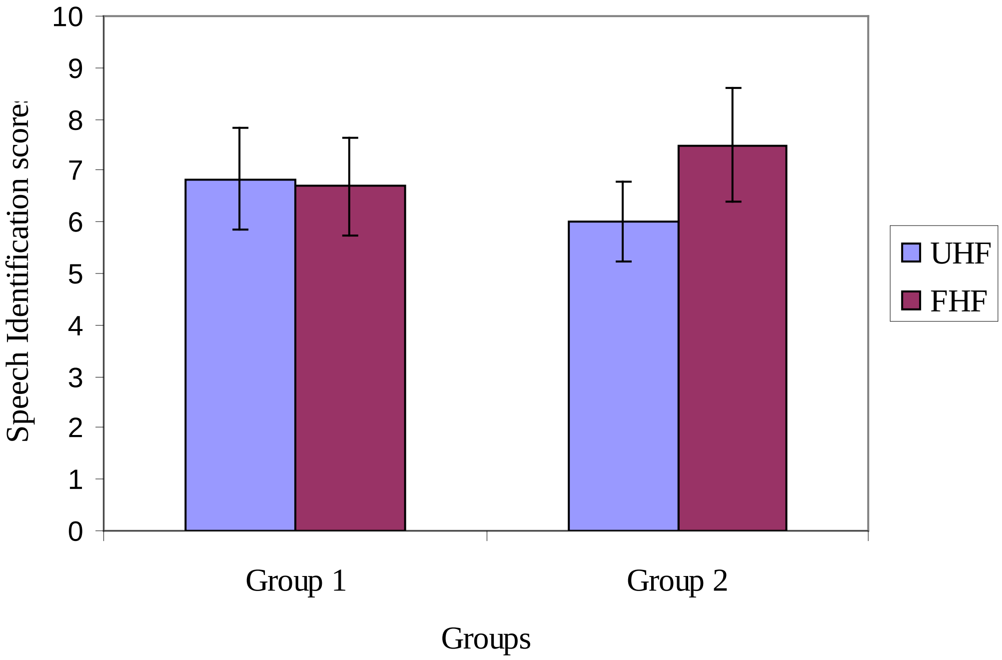

Figure 10. Mean raw speech identification scores for UHF and FHF in Group 1 and Group 2 at corresponding frequency ‘C’ / 4 kHz edge frequency

In general, the overall speech identification scores were better for individuals with cochlear DR as against individuals without cochlear dead regions for the filtered speech stimuli. Also across the edge frequencies/ corresponding frequency start of slope, there was increase in scores with increase in edge frequency/ corresponding frequency form 1 kHz to 4 kHz.

It was observed that there was a significant difference between the speech identification scores of ULF and FLF condition in both Group 1 and Group 2. This was also evident by the increased mean speech identification scores for the filtered condition (Mean: 4.83 and 4.06 for Group 1 and 2 respectively) with the cut-off being 1 kHz as against the unfiltered condition (Mean: 3.75 and 2.62 for Group 1 and 2 respectively). This may be attributed to the fact that the distortion produced due to the off-frequency phenomenon (Patterson & Moore, 1986) may be avoided by filtering the unnecessary frequencies. These effects may reflect cortical plasticity induced changes by the dead regions.

It can also be seen that as the frequency lowered, the scores were poorer, that is, scores were poorer for 1 kHz edge frequency as against 2 kHz and 4 kHz edge frequency. This also shows the use of low frequency information by individuals in both the groups. In 1 kHz, there are limited low frequency regions available and hence the scores were much poorer than 2 kHz and 4 kHz. This has also been supported by Mackersie et al. (2004), who reported that scores dropped as the low-pass filter cutoff was reduced, which indicates that decrease in low frequency input results in poorer scores. Also the similar results as that of the present study have been found by Moore and Vinay (2009) who reported that consonant identification was significantly better for the ears with than without dead regions, with low pass filtering till the edge frequency 1 kHz for individuals with 1 kHz DR. They conclude that a dead region at high frequencies is associated with a better ability to process information at low frequencies.

Similar to the 1 kHz edge frequency, results also showed that there was improved performance with filtered speech in individuals with dead region at 2 kHz and 4 kHz edge frequency. This is also supported by Turner and Brus (2001), who evaluated the effects of providing audible speech information to the low and mid frequency regions for listeners with various degrees of sensorineural hearing loss. Results of their study revealed that below 2.8 kHz, amplification provided positive benefit for recognition scores regardless of degree of loss. These results have also been found in the present study, that is, better scores in filtered condition than the unfiltered condition. Similar studies have also been reported in individuals with high frequency DR, where in their performance was better for low pass filtered speech stimulus than wide band speech stimulus (Vickers et al., 2001; Baer et al., 2002).

Vickers et al. (2001) were amongst the first to examine the benefits of high frequency amplification for people with diagnosed dead regions. The speech was low pass filtered with various cut-off frequencies. For individuals without dead regions, performance generally improved progressively with increasing cut-off frequency up to the highest frequency tested 7.5 kHz. For individuals with dead regions, they observed two patterns of performance. For most individuals, performance initially improved with increasing cut-off frequency and then reached an asymptote. The asymptote was reached when the cut-off frequency was about 1.5–2 times the estimated edge frequency of the dead region. For a few individuals, performance initially improved with increasing cutoff frequency, and then worsened with further increase in the cut-off frequency.

Similarly, Baer et al., (2002) presented the amplified speech to the individuals either broadband upper frequency limit 7.5 kHz or after low pass filtering with various cut-off frequencies. For individuals without a dead region, the cut-off frequencies were chosen to span the range 0.8 kHz 7.5 kHz. Results indicated that for patients without high frequency dead regions, amplification of the high frequencies was beneficial. In individuals without dead regions high scores were obtained for the 7.5 kHz cut-off frequency than for the 3 kHz cut-off frequency.

Similar to the present study, Mackersie et al. (2004) compared threshold-matched ears with and without suspected cochlear dead regions in terms of the speech perception benefit from high-frequency amplification using nonsense vowel-consonant- vowel combinations in wide-band (unfiltered) condition and in the filtered conditions where the speech stimuli were filtered at different cut-off frequencies, in both quiet and noise. Results showed that quiet and in low levels of noise, speech perception scores were significantly higher for the wide-band (unfiltered) condition than for the filtered conditions, and performance was similar for the ears with and without suspected dead regions. In high levels of noise, mean scores were highest in the wide-band condition for the ears without suspected dead regions, but performance reached an asymptote for the ears with suspected dead regions. These results suggest that patients with cochlear dead regions may experience speech perception benefit from wide-band high-frequency gain in quiet and low levels of noise, but not in high levels of noise. Thus, this supports that fact that individuals with DR performance better in filtered conditions than wide band (unfiltered) conditions.

A consonant identification test was carried out with ten hearing-impaired listeners under various low-pass filter conditions by Simpson, McDermott and Dowell (2005). Individuals were also tested for cochlear dead regions with the TEN test. All individuals had moderate-to-severe high-frequency hearing losses. Consonant recognition was tested under conditions in which the speech signals were highly audible to individuals for frequencies up to the low-pass filter cut-off. Extensive dead regions were found for one subject with the TEN test. The remaining individuals may have had dead regions above 3 kHz, because of the severity of their hearing losses, but these could not be demonstrated with the TEN test. Average consonant scores for the subject group improved significantly with increasing audibility of high-frequency components of the speech signal. There were no cases of speech perception being reduced with increasing bandwidth. Nine of the individuals showed improvements in scores with increasing audibility, whereas the remaining subject showed little change in scores. For this individual with DR, speech perception results were consistent with the TEN test findings. Thus, this study shows that individuals without DR make use of the high frequency information, and it is also evident from the present study with increased scores for unfiltered condition, as against individuals with DR, who do not benefit with high frequency information.

There are several theoretical reasons why people with dead regions might extract little or no information from frequency components of speech that fall within a dead region, even if those components are amplified sufficiently to make them audible (Vickers et al., 2001). These reasons include the following:

1. The frequency components are received through the wrong place in the cochlea. When there is a high frequency dead region, amplified high-frequency components will be detected and analyzed via the frequency channels or places that are tuned to lower frequencies. This mismatch between frequency and place may lead to difficulty in interpreting the information derived from the high frequencies. There is some evidence supporting this idea from studies involving the simulation of hearing loss and/or of cochlear implant signal processing (Shannon et al., 1998).

2. If the components falling in the dead region are amplified sufficiently to make them audible, they will be detected and analyzed via the same neural channels that are used for other frequencies, and this may impair the analysis of those other frequencies. For example, if there is a high-frequency dead region, the amplified high frequency components will be detected and analyzed through the same neural channels as are used for the low and medium frequencies.

Since speech is a broadband signal, usually containing components covering a wide frequency range, this may lead to some form of information overload in those channels.

3. Information in speech, such as information about formant frequencies, may partly be coded in the time patterns of the neural impulses called as the phase locking (Young & Sachs, 1979; Miller et al., 1997; Baer & Moore, 1997; Baer et al., 1993). The analysis of temporal information may normally be done on a place-specific basis. For example, the neural machinery required to decode temporal information from frequencies around 2 kHz may be restricted to neural channels with CFs close to 2 kHz (Loeb et al., 1983; Srulovicz & Goldstein, 1983). This is the theoretical rationale behind the measure average localized synchronized rate (Young & Sachs, 1979; Miller et al., 1997). When there is a mismatch between the frequencies of the speech components and the place where they are detected, the temporal decoding mechanisms required to analyze those speech components may not operate effectively.

Results also revealed that there was significant difference in speech identification scores of FMF and FHF in individuals with cochlear dead regions at 2 kHz edge frequency. It was also observed that the mean speech identification scores for FHF was higher (mean = 7.78) as against the mean for speech identification for FMF (mean = 6.85). This can be attributed to the fact that more cues are obtained from the FHF than FMF. FMF has a low pass cut-off of 2 kHz presented to the individuals with edge frequency 2 kHz. It is known that the off-frequency phenomenon is predominant in individuals with DR. This, FMF filtering condition will further create an overload on the mid frequency fibers together with off frequency, which in turn decreases the cues for perception of the stimuli; thus lowering the scores for FMF individuals with 2 kHz DR.

It was also observed that the two unfiltered conditions UMF and UHF were significantly different in individuals without dead regions at corresponding frequency ‘B’ (2 kHz). It was also seen that the mean speech identification score for UHF was higher (Mean = 5.93) than the mean speech identification score for UMF (Mean = 5.30). Higher scores for UHF can be attributed to the fact that the UHF consonants were in the vowel context of /i/ and /e/. This combination will provide more energy than compared to UMF consonants that comprised of /a/ vowel context having relatively lower energy.

Overall, these results support the idea that individuals with dead regions at high frequencies do not make as effective use of audible speech information at high frequencies as individuals without dead regions. Furthermore, the results support the idea that increasing the audibility of speech for frequencies well inside a dead region does not lead to concomitant increases in speech intelligibility.

4.3 Correlation of frequency discrimination scores and speech identification scores in Group 1 and Group 2

To establish the relationship between the frequency discrimination scores and speech identification scores in Group 1 and Group 2 Spearman’s correlation was performed. Results revealed that there was a negative correlation between frequency discrimination and the speech identification scores in Group 1, that is, in individuals without DR . The Table 14 depicts the results for Group 1.

Table 14.

Correlation of frequency discrimination and speech identification scores for Group 1

Frequency discrimination	Speech condition	r*	Significance
F_F	ULF	-0.64	$p<0.05$
F_F	UMF	-0.59	$p<0.01$
F_F	FMF	-0.31	$p<0.05$
F_N	ULF	-0.67	$p<0.05$
F_N	FMF	-0.35	$p<0.05$

**Note. ‘r’ is correlation symbol.*

However there was no correlation between frequency discrimination and the speech scores in Group 2, that is in individuals with DR ($p>0.05$).

The FMDL scores of F_F and F_N correlated well with speech identification scores of ULF, UMF and FMF in Group 1. This is also in support with the fact that the speech identification scores of ULF, UMF and FMF have the same frequency composition as that of frequency of F_F and F_N which ranged from 500 to 3.8 kHz.

There are several studies correlating the frequency selectivity and speech scores in individuals without DR. Dubno, Dirks and Langhofer (1982) suggested there is one to one correlation between the speech recognition errors and audiogram patterns observed.

Preminger and Wiley (1985) reported that the individuals with high frequency loss had broader PTCs at 4 kHz, but normal at 0.5 kHz. These individuals achieved higher performance for low frequency consonants than for high frequency consonants. The individuals with flat hearing losses showed almost no frequency selectivity at 4 kHz and they performed poorly at identifying high frequency consonants. For individuals with low frequency loss, the relation between PTC and consonant identification was also not clear.

Thibodeau and van Tassell (1987) estimated frequency selectivity at 2 kHz by measuring the percentage- correct detection of a 2 kHz sinusoid as a function of the width of spectral notch in a noise, the notch being centered at 2 kHz. Discrimination of /di/ and /gi/ were measured. There was a significant correlation between scores on the two tasks. Individuals with poor frequency selectivity were also poorer at discriminating the syllables.

Dubno, Dirks and Schaefer (1989) evaluated set of consonant recognition in normal hearing listeners and listeners with high frequency hearing loss using Articulation index (AI) theory. The consonants were low pass filtered from 0.1 kHz to 5 kHz and high pass filtered from 355 Hz to 5 kHz. They reported that many of the predictions for the hearing-impaired individuals in the unfiltered condition were within the normal range. In general, the AI tended to overestimate performance for the hearing-impaired listeners. The accuracy of the predictions decreased with the magnitude of high frequency hearing loss or with the rate of change of threshold with frequency. Under filtered conditions AI predictions and scores for hearing-impaired listeners for stimulus bandwidths restricted to regions of normal heating were equivalent to the normal transfer function. Thus, with the exception of performance for listeners with severe high-frequency hearing loss, the results suggest that poorer speech recognition among hearing-impaired listeners results from reduced audibility within critical spectral regions of the speech stimuli.

Ching et al., (1997) examined the relationship between audibility and speech recognition for individuals with sensorineural hearing losses ranging from mild to profound degree of hearing loss. Speech stimuli were presented in both quiet and noise under different filtering conditions. The deviations of the speech scores from the predicted values at high SLs were significantly correlated with a measure of frequency selectivity at 2 kHz.

Similar to the results of the present study, Amos and Humes (2007) revealed that performance for unshaped speech was correlated moderately and negatively with degree of high frequency hearing loss. Alternatively, recognition performance for shaped speech was related to neither the performance for unshaped speech nor the amount of high-frequency hearing loss. Irrespective of degree of high frequency hearing loss, no improvement (or decrease) in word recognition performance emerged that was specifically attributable to the high-frequency band of speech.

However, in individuals without DR, there was absence of any correlation between the frequency discrimination and speech identification scores. Even though the filtered speech scores were significantly higher in individuals with DR as against without DR, there was no correlation seen between the frequency modulation difference limen scores and the speech identification scores. This may be attributed to the mis-match in the frequency place representation due to the presence of off-frequency listening in individuals with DR. Thai-Van et al., (2003) suggested that local improvement in difference limen frequency (DLFs) represents a side effect of neurophysiological mechanisms that have no major perceptual consequences on speech or music perception. This hypothesis of Thai-Van et al., (2003) may be true in individuals with cochlear DR.

Hence the results of the present study can be summarized as follows:

- There was enhanced frequency discrimination in individuals with cochlear dead regions near the edge frequency as against individuals without dead region.
- Individuals with cochlear dead region performed better in the speech identification testing for the filtered conditions, with filter cut-off being the frequency of the edge frequency.
- As the edge frequency/ start of slope was higher (2 kHz and 4 kHz) performance on speech identification scores improved as against 1 kHz edge frequency/ corresponding frequency ‘A’.
- There was a negative correlation found between the frequency modulation difference limen scores and speech identification scores in individuals without cochlear dead region as against in individuals with cochlear dead region.

CHAPTER 5

SUMMARY AND CONCLUSIONS

CHAPTER 5

Summary and Conclusions

Cochlear hearing loss has many causes and it is often seen that the damage is caused to the outer hair cells (OHCs) and inner hair cells (IHCs) in the cochlea. A dead region (DR) can be defined as a region in the cochlea where the IHCs and/or neurons are functioning very poorly, if at all present. Dead region is often described in terms of the edge frequency (*fe*). It is seen from earlier research that the presence of dead region led to improved frequency discrimination near the edge frequency. The present study aimed at analyzing the frequency discrimination across the edge frequencies in individuals with dead regions and start of slope matched individuals without cochlear dead regions. The study also aimed at measuring the speech identification scores under unfiltered and filtered conditions and also to correlate the frequency discrimination scores and the speech identification scores in individuals with and without dead regions.

A total of 52 participants (82 ears) were taken for the study. They were divided into two groups; Group 1 which consisted of 38 ears with sensorineural hearing loss without cochlear dead region and Group 2 consisted of 44 ears with sensorineural hearing loss with cochlear dead region. Threshold Equalizing Noise (TEN) test was administered to diagnose the presence or absence of dead regions. Frequency modulation difference limen (FMDL) was administered to obtain the frequency discrimination scores. Speech identification test was administered using the consonant-vowel combinations (CVs) which were grouped based on their frequency composition as low, mid and high frequency stimuli. The stimuli were used without filtering called the unfiltered condition and the other being the filtered condition with the cut-off frequency being the edge frequency/ corresponding frequency at start of slope.

The data obtained was analysed using the statistical tests, Mixed ANOVA, Two - way ANOVA and paired t- tests. Analysis revealed that FMDL scores were lower (better) for individuals without dead regions near the edge frequency as against individuals without dead regions. It was also noticed that as the edge frequency was lower, that is at 1 kHz, the FMDL scores were higher (worse) as against 4 kHz in individuals with and without cochlear dead regions. These results also suggest that the enhanced frequency discrimination near the edge frequency in individuals with cochlear dead regions, which was due to cortical re-organization.

The speech identification scores were better for filtered conditions, with cut - off being the frequency of the edge, in individuals with dead regions at edge frequency 1 kHz and 4 kHz. These results again reveal that the individual with dead regions do make use of the full band speech information specially the high frequency information and the identification improves in the filtered conditions with the filter cut- off being the frequency of the edge.

There was some correlation between the frequency discrimination scores and speech identification scores in both filtered and unfiltered conditions in individuals without dead regions as against in individuals with dead regions. This may be due to the mis-match in the frequency- place representation due to the presence of off-frequency listening in individuals with DR.

Thus, it can be concluded that there is enhanced frequency discrimination near the edge frequency due to cortical re-organization in individuals with cochlear dead regions and they perform well in the filtered speech conditions with filter cut-off being the edge frequency. However there is no correlation between the frequency-place information in individuals with cochlear dead regions.

Implications for future research:

- The study can be replicated with different speech filtering conditions and estimating the condition where the individuals with cochlear dead region perform the best and the condition which best correlates with the frequency discrimination.
- Speech material in the form of words and sentences can be taken and filtered sharply without degrading the stimuli and can be used to find the correlation of speech identification scores and frequency discrimination abilities.
- Similar studies can also be carried out with amplification/ hearing aids.

CHAPTER 6

REFERENCES

CHAPTER 6

References

Aazh, H., & Moore, B. C. J. (2007). Dead regions in the cochlea at 4 kHz in elderly adults: Relation to absolute threshold, steepness of audiogram, and pure tone average. *Journal of American Academy of Audiology*, *18*, 96–107.

Alexander, G. C., Cox, R. M., Rivera, I., Johnson, J., & Gardino, J. (2007). *Prevalence of cochlear dead regions among adult hearing-impaired patients*. Refereed poster presented at the Annual Meeting of the American Auditory Society, Scottsdale, AZ.

American National Standards Institute. (1999). *Maximum permissible ambient noise for audiometric test rooms* (ANSI S3.1-1999). New York: ANSI.

Amos, N. E., & Humes, L. E. (2007). Contribution of high frequencies to speech recognition in quiet and noise in listeners with varying degrees of high-frequency sensorineural hearing loss. *Journal of Speech, Language and Hearing Research*, *50* (4), 819-834.

Apoorva, H. M., Kruthika, S., & Saranya,V. (2009). Intensity discrimination in individuals with and without cochlear dead regions. Paper presented at the 41st Indian Speech and Hearing Association Conference (ISHACON), Pune.

Baer, T., Moore, B.C.J. (1997). Evaluation of a scheme to compensate for reduced frequency selectivity in hearing impaired subjects. In: Jesteadt, W. (Ed.), *Modeling Sensorineural Hearing Loss*. New Jersey: Erlbaum.

Baer, T., Moore, B. C. J., & Kluk, K. (2002). Effects of low pass filtering on the intelligibility of speech in noise for people with and without dead regions at high frequencies. *Journal of Acoustical Society of America, 112,* 1133-1144.

Burns, E., & Williamson, S. J. (1981). Pitch intensity functions in impaired ears. *Journal of the Acoustical Society of America, (Suppl. 69),* 565-571.

Buss, E., Hall, J. W., Grose, J. H., & Hatch, D. R. (1998). Perceptual consequences of peripheral hearing loss: do edge effects exist for abrupt cochlear lesions? *Hearing Research*, *125*, 98-108.

Carhart, R. (1945). Classifying audiograms: An improved method for classifying audiograms. *Laryngoscope, 55*, 640-662

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

Ching, Y. C. T., Dillon, H., & Byrne, D. (1997). Prediction of speech recognition from audibility and psychoacoustic abilities in hearing – impaired listeners. In

Jesteadt (Eds.), *Modeling sensorineural hearing loss* (pp. 433-445). New Jersey: Erlbaum.

Ching, Y. C. T., Dillon, H., & Byrne, D. (1998). Speech recognition of hearing-impaired listeners: Predictions from audibility and the limited role of high-frequency amplification. *Journal of Acoustical Society of America, 103* (2), 1128-1140.

Dietrich, V., Nieschalk, M., Stoll, W., Rajan, R., & Pantev, C. (2001). Cortical reorganization in patients with high frequency cochlear hearing loss. *Hearing Research, 158*, 95-101.

Dreschler, W. A. & Plomp, R. (1980). Relations between psychological data and speech perception for hearing impaired individuals. I. *Journal of Acoustical Society of America, 68,* 1608-1615.

Dreschler, W. A. & Plomp, R. (1985). Relations between psychological data and speech perception for hearing impaired individuals. II. *Journal of Acoustical Society of America, 78,* 1261- 1270.

Dubno, J.R., Dirks, D.D., & Langhofer, L.R. (1982). Evaluation of hearing-impaired listeners using a Nonsense-syllable Test. II. Syllable recognition and consonant confusion patterns. *Journal of Speech and Hearing Research, 25* (1), 141-148.

Dubno, J. R., Dirks, D. D., & Ellison, D. E. (1989). Stop-consonant recognition for normal-hearing listeners and listeners with high-frequency hearing loss. I: The contribution of selected frequency regions. *Journal of Acoustical Society of America, 85*(1), 355-364.

Dubno, J.R., Dirks, D.D., & Schaefer, A. B. (1989). Stop-consonant recognition for normal-hearing listeners and listeners with high-frequency hearing loss. II : Articulation index predictions. *Journal of Acoustical Society of America, 85*(1), 347-354.

Ehmer, R. H. (1959a). Masking patterns of tones. *Journal of Acoustical Society of America, 31*, 1115-1120.

Evans, E. F. (1978). Place and time coding of frequency in the peripheral auditory system: some physiological pros and cons. *Audiology, 17*, 369-420.

Florentine, M., & Houtsma, A. J. M. (1983). Tuning curves and pitch matches in a listener with a unilateral, low-frequency hearing loss. *Journal of Acoustical Society of America, 73*, 961-965.

Florentine, M., Reed, C.M., Rabenowitz, W.H., Braede, L.D. & Durlach, N. (1993). Intensity perception, XIV. Intensity discrimination in listeners with sensorineural hearing loss. *Journal of Acoustical Society of America, 94,* 2575-2586.

Glasberg, B. R., & Moore, B. C. J. (1986). Auditory filter shapes in individuals with unilateral and bilateral cochlear impairments. *Journal of Acoustical Society of America, 79,* 1020-1033.

Glasberg, B. R., & Moore, B. C. J. (1989). Psychoacoustic abilities of individuals with unilateral and bilateral cochlear impairments and their relationship to the ability to understand speech. *Scandinavian Audiology (Suppl.), 32,* 1-25.

Glasberg, B. R., & Moore, B. C. J. (1990). Derivation of auditory filter shapes from notched noise data. *Hearing Research, 47,* 103-138.

Greenwood, D. D. (1971). Aural combination tones and auditory masking. *Journal of Acoustical Society of America*, *50,* 502-543.

Halpin, C., Thornton, A., & Hasso, M. (1994). Low-frequency sensorineural loss: Clinical evaluation and implications for hearing aid fitting. Ear and Hearing, 15, 71-81.

Hoekstra, A., & Ritsma, R. J. (1977). Perceptive hearing loss and frequency selectivity. In: Evans, E. F., & Wilson, J. P. (Eds.), *Psychophysics and Physiology of Hearing,* (pp. 263-271). London: Academic Press.

Hogan, C., & Turner, C. W. (1998). High-frequency amplification: Benefits for hearing-impaired listeners. *Journal of Acoustical Society of America, 104,* 432–44.

Horst, J. W. (1987). Frequency discrimination of complex signals, frequency selectivity and speech perception in hearing impaired individuals. *Journal of Acoustical Society of America, 82,* 874-885.

Horwitz, A.R., Dubno, J.R., & Ahlstrom, J.B. (2002). Recognition of low pass filtered consonants in noise with normal and impaired high frequency hearing. *Journal of Acoustical Society of America, 111* (1), 409-416.

Huss, M., & Moore, B. C. J. (2003). Tone decay for hearing-impaired listeners with and without dead regions in the cochlea. *Journal of Acoustical Society of America, 114*, 3283-3294.

Huss, M., & Moore, B. C. J. (2005). Dead regions and pitch perception. *Journal of Acoustical Society of America, 117,* 3841-3852.

Huss, M., & Moore, B. C. J. (2005a). Dead regions and pitch perception. *Journal of Acoustical Society of America, 117,* 3841-3852.

Huss, M., Moore, B. C. J. (2005b). Dead regions and noisiness of pure tones. *International Journal of Audiology, 44*, 599-611.

Irvine, D. R. F., & Rajan, R. (1995). Plasticity in the mature auditory system. In: Manley, G. A., Klump, G. M., Köppl, C., Fastl, C., Oeckinghaus, H. (Eds.), (pp 3–23). *Advances in hearing research.* Singapore: World Scientific.

Irvine, D. R. F., Rajan, R., Brown, & Mel (2001) Injury- and Use-Related Plasticity in Adult Auditory Cortex. *Audiology & Neuro-Otology, 6*(4), 192-195.

Joris, P. X., Carney, L. H., Smith, P. H., & Yin, T. C. (1994). Enhancement of neural synchronization in the anteroventral cochlear nucleus I. Responses to tones at the characteristic frequency. *Journal of Neurophysiology, 71,* 1022–1036.

Kiang, N. Y., & Moxon, E. C. (1974). Tails of tuning curves of auditory-nerve fibers. *Journal of American Academy of Audiology, 55,* 620-630.

Kluk, K., & Moore, B. C. J. (2004). Factors affecting psychophysical tuning curves for normally hearing individuals. *Hearing Research, 194,* 118-134.

Kluk, K. (2005). *Measuring and characterizing dead regions*. Unpublished Doctoral Dissertation, University of Cambridge, Cambridge.

Kluk, K., & Moore, B. C. J. (2005). Factors affecting psychophysical tuning curves for hearing-impaired individuals with high-frequency dead regions. *Hearing Research, 200,* 115- 131.

Kluk, K., & Moore B. C. J. (2006) Dead regions in the cochlea and enhancement of frequency discrimination: Effects of audiogram slope, unilateral versus bilateral loss, and hearing-aid use. *Hearing Research, 222*(1-2), 1-15.

Kluk K. & Moore B.C.J. (2006b). Detecting dead regions using psychophysical tuning curves: A comparison of simultaneous and forward masking. *International Journal of Audiology, 45*, 463-476.

Liberman, M. C. & Dodds, L. W. (1984). Single neuron labeling and chronic cochlea pathology. III. Stereocilia damage and alternations in threshold tuning curves. *Hearing Research, 16*, 54-74.

Loeb, G. E., White, M. W. & Merzenich, M. M. (1983). Spatial cross correlation: A proposed mechanism for acoustic pitch perception. *Biological cybernetics, 47,* 149-163.

Lutman, M. E. (1991). Degradations in frequency and temporal resolution with age and their impact on speech identification. *Acta Oto-Laryngologica (Suppl. 4),* 120-126.

Mackersie, C. L., Crocker, T. L., & Davis, R. A. (2004). Limiting high-frequency hearing aid gain in listeners with and without suspected cochlear dead regions. *Journal of American Academy of Audiology, 15*, 498-507.

McDermott, H. J., Lech, M., Kornblum, M. S., & Irvine, D. R. F. (1998). Loudness perception and frequency discrimination in individuals with steeply sloping hearing loss: Possible correlates of neural plasticity. *Journal of Acoustical Society of America, 104,* 2314-2325.

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

Moore, B. C. J. (1978). Psychophysical tuning curves measured in simultaneous and forward masking. *Journal of Acoustical Society of America*, *63,* 524-532.

Moore, B. C. J. (1998). *Cochlear Hearing Loss,* Whurr, London.

Moore, B. C. J. (2001). Dead regions in the cochlea: Diagnosis, perceptual consequences, and implications for the fitting of hearing aids. *Trends in Amplification*, *5*, 1-34.

Moore, B. C. J. (2003). *An Introduction to the Psychology of Hearing* (5th ed.). SanDiego: Academic Press.

Moore, B. C. J. (2004). Dead regions in the cochlea: conceptual foundations, diagnosis, and clinical applications. *Ear and Hearing, 25*(2), 98-116.

Moore, B. C. J. (2004a). Dead regions in the cochlea: Conceptual foundations, diagnosis and clinical applications. *Ear and Hearing, 25,* 98-116.

Moore, B. C. J. (2004b). Testing the concept of softness imperception: Loudness near threshold for hearing-impaired ears. *Journal of Acoustical Society of America*, *115,* 3103-3111.

Moore, B. C. J., & Alcántara, J. I. (2001). The use of psychophysical tuning curves to explore dead regions in the cochlea. *Ear and Hearing*, *22,* 268-278.

Moore, B. C. J. & Carlyon, R. P. (2005). *Perception of pitch by people with cochlear hearing loss and by cochlear implant users.* In: Plack, C. J., Oxenham, A. J., Fay, R. R., Popper, A. N. (Eds.), Pitch perception, Springer, New York, pp. 234-277.

Moore, B. C. J. & Glasberg, B. R. (1986). Comparisons of frequency selectivity in simultaneous and forward masking for individuals with unilateral cochlear impairments. *Journal of Acoustical Society of America*, *80,* 93-107.

Moore, B. C. J. & Glasberg, B. R. (1997). A model of loudness perception applied to cochlear hearing loss. *Auditory Neuroscience*, *3,* 289-311.

Moore, B. C. J. & Skrodzka, E. (2002). Detection of frequency modulation by hearing impaired listeners: Effects of carrier frequency, modulation rate, and added amplitude modulation. *Journal of Acoustical Society of America*, *111,* 327-335.

Moore, B. C. J., Alcántara, J. I., Dau, T. (1998). Masking patterns for sinusoidal and narrowband noise maskers. *Journal of Acoustical Society of America, 104,* 1023-1038.

Moore, B. C. J., Glasberg, B. R., & Stone, M. A. (2004). New version of the TEN test with calibrations in dB HL. *Ear and Hearing, 25,* 478-487.

Moore, B. C. J., Huss, M., Vickers, D. A., Glasberg, B. R., & Alcántara, J. I. (2000). A test for the diagnosis of dead regions in the cochlea. *British Journal of Audiol*ogy*, 34,* 205-224.

Moore, B. C. J., Killen, T., & Munro, K. J. (2003). Application of the TEN test to hearing impaired teenagers with severe to profound hearing loss. *International Journal of Audiology, 42,* 465-474.

Moore, B. C. J., Laurence, R. F., & Wright, D. (1985). Improvements in speech intelligibility in quiet and in noise produced by two-channel compression hearing aids. *British Journal of Audiology, 19,* 175-187.

Moore, B. C. J., & Vinay (2009). Enhanced discrimination of low-frequency sounds for subjects with high-frequency dead regions. *Brain, 132*, 524-536.

Munro, K. J. & Trotter, H. (2006). Preliminary evidence of asymmetry in uncomfortable loudness levels after unilateral hearing aid experience: Evidence of functional plasticity in the adult auditory system. In Kluk, K. (2005).

Measuring and characterizing dead regions. Unpublished doctoral thesis, University of Cambridge, Cambridge.

Murray, N. & Byrne, D. (1986). Performance of hearing-impaired and normal hearing listeners with various high-frequency cut-offs in hearing aids. *Australian Journal of Audiology, 8*, 21-28.

Patterson, R. D., & Moore, B. C. J. (1986). Auditory filters and excitation patterns as representations of frequency resolution. In: Moore, B. C. J. (Eds.), *Frequency Selectivity in Hearing* (pp. 123-177). London: Academic.

Patterson, R. D., Nimmo-Smith, I., Weber, D. L., & Milroy, R. (1982). The deterioration of hearing with age: frequency selectivity, the critical ratio, the audiogram, and speech threshold. *Journal of the Acoustical Society of America, 72*, 1788-1803.

Philibert, B., Collet, L., Vesson, J. F., Veuillet, E. (2005). The auditory acclimatization effect in sensorineural hearing-impaired listeners: evidence for functional plasticity. *Hearing Research, 205*, 131-142.

Pick, G., Evans, E.F., Wilson, J.P. (1977). Frequency resolution in patients with hearing loss of cochlear origin. In: Evans, E.F., Wilson, J.P. (Eds.), Psychophysics and Physiology of Hearing. Academic Press, London.

Ponton, C. W., Vasama, J. P., Tremblay, K., Khosla, D., Kwong, B., Don, M. (2001). Plasticity in the adult human central auditory system: evidence from late-onset profound unilateral deafness. *Hearing Research, 154*, 32-44.

Preminger, J. E., & Wiley, T. L. (1985). Frequency selectivity and consonant intelligibility in sensorineural hearing loss. *Journal of Speech and Hearing Research, 28,* 197-206.

Preminger, J. E., Carpenter, R., & Ziegler, C. H. (2005). A clinical perspective on cochlear dead regions: Intelligibility of speech and subjective hearing aid benefit. *Journal of American Academy of Audiology, 16*, 600-613.

Punch, J.L., & Beck, E.L. (1980). Low-frequency response of hearing aids and judgments of aided speech quality. *Journal of Speech and Hearing Disorders, 45,* 325-335.

Punch, J. L., Montgomery, A. A., Schwartz, D. M., Walden, B. E., Prosek, R. A., & Howard, M. T. (1980). Multidimensional scaling of quality judgments of speech signals processed by hearing aids. *Journal of the Acoustical Society of America, 68,* 458-466.

Rajan, R. & Irvine, D. R. (1998b). Neuronal responses across cortical field A1 in plasticity induced by peripheral auditory organ damage. *Audiology and Neuro-otology, 3,* 123-144.

Rajan, R., Irvine, D. R. F., Wise, L. Z., & Heil P. (1993). Effect of unilateral partial cochlear lesions in adult cats on the representation of lesioned and unlesioned cochleas in primary auditory cortex. *Journal of Computational Neurology*, *338,* 17- 49.

Ramaswami, N. (1999). *Common linguistic feature identification in Indian languages: Phonetics.* CIIL: CIIL printing press.

Robertson, D., & Irvine, D. R. F. (1989). Plasticity of frequency organization in auditory cortex of guinea pigs with partial unilateral deafness. *Journal of Computational Neurology*, *282,* 456-71.

Robinson, K. & Gatehouse, S. (1996). The time course of effects on intensity discrimination following monaural fitting of hearing aids. *Journal of American Academy of Audiology*, *99,* 1255-1258.

Ruggero, M. A. (1992). Responses to sound of the basilar membrane of the mammalian cochlea. *Current opinion in neurobiology*, *2,* 449-456.

Ruggero, M. A. (1994). Cochlear delays and traveling waves: Comments on ‘Experimental look at cochlear mechanics, *Audiology*, *33,* 131-124.

Ruggero, M. A., Rich, N. C., Robles, L., Recio, A. (1996). The effects of acoustic trauma, other cochlea injury and death on basilar membrane responses to sound. In: Axelsson, A., Borchgrevink, H., Hamernik, R. P., Hellstrom, P. A., Henderson, D., Salvi, R. J. (Eds.), *Scientific Basis of Noise-Induced Hearing Loss* (pp. 23-35). Stockholm: Thieme.

Salvi, R., Wang, J., & Ding, D. (2000). Auditory plasticity and hyperactivity following cochlear damage. *Hearing Research, 147*, 261-274.

Santurette & Dau (2007). Binaural pitch perception in normal-hearing and hearing-impaired listeners. *Hearing Research, 223*(1-2), 29-47.

Scheffler, K., Bilecen, D., Schmid, N., Tschopp, K., & Seelig, J. (1998). Auditory cortical responses in hearing individuals and unilateral deaf patients as detected by functional magnetic resonance imaging. *Cerebral Cortex, 8,* 156-163.

Schroder, A.C.,Viemeister, N.F. & Nelson, D.A. (1994). Intensity discrimination in normal hearing and hearing impaired listeners. *Journal of the Acoustical Society of America, 96,* 2683-2673.

Schwaber, M. K., Garraghty, P. E., & Kaas, J. H. (1993). Neuroplasticity of the adult primate auditory cortex following cochlear hearing loss. *American Journal of Otology, 14,* 252-258.

Schwartz, D. M., Surr, R. K., Montgomery, A. A., Prosek, R. A., & Walden, B. E. (1979). Performance of high frequency impaired listeners with conventional and extended high frequency amplification. *Audiology, 18*(2), 157-174.

Sek, A., Alcántara, J. I., Moore, B. C. J., Kluk, K., & Wicher, A. (2005). Development of a fast method for determining psychophysical tuning curves. *International Journal of Audiology,* 408- 420.

Shamma, S., & Klein, D. (2000). The case of the missing pitch templates: how harmonic templates emerge in the early auditory system. *Journal of Acoustical society of America*, *107*, 2631- 2644.

Simon, H. J., & Yund, E. W. (1993). Frequency Discrimination in listeners with sensorineural hearing loss. *Ear and Hearing, 14,* 190-199.

Simpson, A., McDermott, H.J., & Dowell, R.C. (2005). Benefits of audibility for listeners with severe high-frequency hearing loss. *Hearing Research, 201(1-2),* 42-52.

Skinner, M. W. (1980). Speech intelligibility in noise in noise-induced hearing loss: effects of high frequency compensation. *Journal of Acoustical Society of America*, *67,* 306–317.

Skinner, M. W., & Miller, J.D. (1983). Amplification bandwidth and intelligibility of speech in quiet and noise for listeners with sensorineural hearing loss. *Audiology*, *22,* 253-259.

Stelmachowicz, P.G., Jesteadt,W., Gorga, P.M., & Mott, J. (1985). Speech perception ability and psychophysical tuning curves in hearing-impaired listeners. *Journal of acoustical society of America*, *77* (2), 620-627.

Srulovicz, P. & Goldstein, J. L. (1983). A central spectrum model: a synthesis of auditory nerve timing and place cues in monaural communication of frequency spectrum. *Journal of Acoustical Society of America*, *73,* 1266-1276.

Summers, V., Molis, M. R., Musch, H., Walden, B. E., Surr, R. K., & Cord, M. T. (2003). Identifying dead regions in the cochlea: psychophysical tuning curves and tone detection in threshold-equalizing noise. *Ear and Hearing, 24,* 133-142.

Sullivan, Allsmas, Moblay (1992). Amplification for listeners with steeply sloping hearing loss. *Ear and Hearing, 13,* 35-45.

Thai-Van, H., Micheyl, C., Norena, A., & Collet, L. (2002). Local improvement in auditory frequency discrimination is associated with hearing-loss slope in individuals with cochlear damage. *Brain, 125,* 524-37.

Thai-Van, H., Micheyl, C., Moore, B. C. J., & Collet, L. (2003). Enhanced frequency discrimination near the hearing loss cutoff: A consequence of central auditory plasticity induced by cochlear damage? *Brain, 126*, 2235-2245.

Thai-Van H, Micheyl, C., Norena, A., Veuillet, E., Gabriel, D., & Collet, L. (2007). Enhanced frequency discrimination in hearing-impaired individuals: a review of perceptual correlates of central neural plasticity induced by cochlear damage. *Hearing Research, 233* (1-2), 14-22.

Thibodeau, L. M., & van Tasell, D. J. (1987). Tone detection and synthetic speech discrimination in band-reject noise by hearing-impaired listeners. *Journal of Acoustical Society of America*, *82*, 864-873.

Thornton, A. R., & Abbas, P. J. (1980). Low-frequency hearing loss: perception of filtered speech, psychophysical tuning curves, and masking. *Journal of Acoustical Society of America*, *67,* 638-643.

Turner, C. W., Burns, E. M., & Nelson, D. A. (1983). Pure tone pitch perception and low frequency hearing loss. *Journal of Acoustical Society of America*, *73,* 966-975.

Turner, C. W., & Cummings, K. J. (1999). Speech Audibility for Listeners with High-Frequency Hearing Loss. *American Journal of Audiology, 8*, 47–56.

Turner, C. W., & Brus, S. L. (2001). Providing low- and mid-frequency speech information to listeners with sensorineural hearing loss. *Journal of Acoustical Society of America, 109*(6), 2999-3006.

Turner, C., & Henry, B. (2002). Benefits of amplification for speech recognition in background noise. *Journal of the Acoustical Society of America, 112*, 1675–1680.

Tyler, R. S., Summerfield, A. Q., Wood, E. J., & Fernandes, M. A. (1982). Psychoacoustics and phonetic temporal processing in normal and hearing-impaired listeners. *Journal of the Acoustical Society of America, 72,* 740-752.

Van Rooij, J. C. G. M., & Plomp, R. (1990). Auditive and cognitive factors in speech perception by elderly listeners. II. Multi-variate analysis. *Journal of the Acoustical Society of America, 88,* 2611-2624.

Van Tasell, D. J., & Turner, C. W. (1984). Speech recognition in a special case of low frequency hearing loss. *Journal of Acoustical Society of America, 75,* 1207-1212.

Vasama, J. P., & Makela, J. P. (1995). Auditory pathway plasticity in adult humans after unilateral idiopathic sudden sensorineural hearing loss. *Hearing Research, 87,* 132-140.

Vestergaard, D. M. (2003). Dead regions in the cochlea: Implications of speech recognition and applicability of articulation index theory. *International Journal of Audiology, 42,* 249-261.

Vickers, D. A., Baer, T., & Moore, B. C. J. (2001). Effects of lowpass filtering on speech intelligibility for listeners with dead regions at high frequencies. *British Journal of Audiology, 35,* 148-149.

Vickers, D. A., Moore, B. C. J., & Baer, T. (2001). Effects of lowpass filtering on the intelligibility of speech in quiet for people with and without dead regions at high frequencies. *Journal of the Acoustical Society of America, 110,* 1164-1175.

Vickers, D., Baer, T., Füllgrabe, C., Vinay and Moore, B.C.J. (2006). *"Band-importance functions for normal-hearing & hearing-impaired listeners".* Presentation at the International Hearing Aid Conference held during August 16-20, 2006, at Lake Tahoe, California, USA.

Vinay, & Moore, B. C. J. (2007a). Prevalence of dead regions in individuals with sensorineural hearing loss. *Ear and Hearing, 28*, 231–241.

Vinay, & Moore B. C. J. (2007b). Speech recognition as a function of high pass filter cut-off frequency for subjects with and without low frequency cochlear dead regions. *Journal of Acoustical Society of America, 122,* 542-553.

Vogten, L. L. M. (1974). Pure-tone masking: A new result from a new method. In: Zwicker, E., Terhardt, E. (Eds.). *Facts and Models in Hearing* (pp. 142-155). Berlin: Springer-Verlag.

Wegel, R. L. & Lane, C. E. (1924). The auditory masking of one sound by another and its probable relation to the dynamics of the inner ear. *Phys. Rev, 23,* 266-285.

Willott, J. F. (1991). *Aging and auditory system.* San Diego: Singular Publishing group.

Woolf, N. K., Ryan, A. F., Bone, R. C. (1981). Neural phase-locking properties in the absence of outer hair cells. *Hearing Research, 4,* 335- 346.

Yates, G. K. (1995). Cochlear structure and function. In B. C. J. Moore (Ed.), *Hearing* (pp. 41-73). San Diego: Academic Press.

Young, E. D. & Sachs, M. B. (1979). Representation of steady-state vowels in the temporal aspects of the discharge patterns of populations of auditory-nerve fibers. *Journal of Acoustical Society of America, 66,* 1381–1403.

Zurek, P. M. & Formby, C. (1981). Frequency Discrimination ability of hearing -impaired listeners. *Journal of Speech and Hearing Research, 24*, 108-112.

Zwicker, E., & Schorn, K. (1978). Psychoacoustical tuning curves in Audiology. *Audiology, 17*, 120-140.