SPEECH PERCEPTION WITH AND WITHOUT AMPLIFICATION IN INDIVIDUALS WITH COCHLEAR DEAD REGIONS

DOCTORAL THESIS

By

S. N. Vinay

Under the guidance of

Prof. C.S. Vanaja

Submitted to the University of Mysore in 2007

DEDICATED

TO

CHINNA

CERTIFICATE

This is to certify that the thesis entitled, **Speech Perception with and without Amplification in Individuals with Cochlear Dead Regions,** submitted by S.N.Vinay, for the degree of Doctor of Philosophy in Speech and Hearing to the University of Mysore, was carried out at All India Institute of Speech and Hearing, Mysore under my guidance.

Place: Mysore .

Date: 08 SEPTEMBER 2007

Dr.C.S.Vanaja
Professor in Audiology
Bharathi Vidyapeeth University School of
Audiology & Speech Language Pathology,
Pune-43.

CERTIFICATE

This is to certify that the thesis entitled, **Speech Perception with and without Amplification in Individuals with Cochlear Dead Regions,** submitted by S.N.Vinay, for the degree of Doctor of Philosophy in Speech and Hearing to the University of Mysore, was carried out at All India Institute of Speech and Hearing, Mysore.

Place: Mysore

Date: 20/09/07

Dr. Vijayalakshmi Basavaraj
Director
AIISH, Mysore

DECLARATION

I declare that this thesis entitled, Speech **Perception with and without Amplification in Individuals with Cochlear Dead Regions,** which is submitted herewith for the award of the degree of Doctor of Philosophy in the field of Speech and Hearing to the University of Mysore, Mysore, is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysore, under the guidance of Dr.C.S.Vanaja, Professor in Audiology. I further declare that the results of this work have not been previously submitted for any degree.

Place: Mysore

Date: 08 SEPTEMBER 2007

Vinay

Vinay S.N

ACKNOWLEDGEMENTS

This research work was supported by the AIISH fellowship awarded by the All India Institute of Speech and Hearing, Mysore, India. This work was carried out at the Department of Audiology, All India Institute of Speech and Hearing, Mysore, India.

My sincere regards and respect are due to my guide and mentor, Prof. C.S. Vanaja. She has been a constant inspiration at every stage of this work, sharing her valuable expertise thoughts and knowledge. My deepest gratitude and sincere thanks for understanding and support.

I thank Dr. Vijayalakshmi Basavaraj, Director, All India Institute of Speech and Hearing, Mysore, India for providing the facilities to carry out the research work.

I thank Prof. M. Jayaram, Ex-Director, All India Institute of Speech and Hearing, Mysore, India for giving me an opportunity to take up the fellowship and inspiring my thoughts at several stages of this work.

My sincere thanks are also due to Prof. Asha Yathiraj, who provided valuable help in procuring the hearing aids to be used in the study.

I thank Prof. Brian C.J. Moore, University of Cambridge for providing valuable suggestions and enriching my knowledge in the field of research.

I thank Dr. K. Rajalakshmi, for her valuable help at various stages of the thesis.

I thank Ms. P. Manjula and Mr. Animesh Barman, for being so patient in clarifying any of my doubts regarding the thesis and for providing valuable support.

I thank the Doctoral committee for offering useful suggestions regarding the work.

My sincere gratitude to Ms. Vasanthalakshmi, Dr. Venkatesan, Dr. Jayaram and Mr. Lancy D'Souza for sharing their valuable knowledge in Statistics.

My sincere thanks to all faculty members and one and all in All India Institute of Speech and Hearing, Mysore, India and in the field of Speech and Hearing in general.

I thank and owe a lot to Mr. Mahadeva, Mr. Lokesh, Mr. Nanjunda Swamy, Mr.Ananthaswamy, Mr.Chowdaiah and to my sweet friend Mr. Raju. My sincere thanks to Mr. Shivappa and Mr. Prasad for their valuable help throughout the work.

My parents, chinna and dearest brother inspired me to pursue the doctoral studies. I thank you all for always being with me during my good and bad times. You all deserve special thanks. My dear Swathi Navchethana you deserve special appreciation.

Last but not the least, I thank the ALMIGHTY and all my subjects who agreed to participate in the research work. I thank one and all.

SUBJECT INDEX

TABLE INDEX

FIGURE INDEX

CHAPTER I

INTRODUCTION

"A person whose hearing loss has decreased his or her ability to understand speech may feel isolated—separated from social activities, from family, and from friends by a decreased capacity to communicate. This unwanted solitude may be the most debilitating aspect of hearing loss

(Tobias, 1977, p.37)"

Hearing loss caused due to the damage of the cochlea is the most common form of hearing loss. Cochlear hearing loss involves damage to the sensory mechanism that comprises of outer hair cells and inner hair cells. Studies show that the functioning of the normal cochlea depends upon the operation of an active mechanism that is linked to the integrity of the outer hair cells (Moore, 1998; Ruggero, Rich, Recio, Narayan, & Robles, 1997). The inner hair cells are the transducers of the cochlea converting the mechanical vibrations on the basilar membrane created by outer hair cell activity into neural activity. Damage to the outer hair cells results in elevation of absolute thresholds and leads to a reduction in the compressive function of the outer hair cells (Moore, 1998). The amount of hearing loss due to damage of outer hair cells alone can be up to 50 dB HL at low frequencies and up to 65 dB HL at high frequencies (Ruggero et al., 1997; Yates, 1990). Losses greater than this degree imply partial or total inner hair cells damage. A region in the cochlea where the inner hair cells and/or neurones are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening is called a 'dead region' (Moore, 2004). The extent of a dead region can be defined in terms of the characteristic frequencies of the inner hair cells and/or neurones immediately adjacent to the dead region (Moore, 2001). The characteristic frequency just adjacent to the dead region, at which there are surviving inner hair cells, defines the edge frequency (*fe)* of the dead region (Moore, 2001). In subjects with dead regions, basilar-membrane vibration is not detected via the neurons directly innervating that region but is heard through phenomenon of off-frequency listening (Patterson & Nimmo-Smith, 1980).

Sensorineural hearing impairment with or without dead regions is often accompanied by reduced understanding of speech. There has been considerable controversy in the literature regarding the reasons for reduced speech recognition abilities in subjects with hearing impairment. Elevated sensitivity thresholds leading to the inaudibility of speech is a major contributing factor for poor understanding of speech. However, for subjects with more severe hearing losses, providing equivalent speech information at suprathreshold levels to subjects with normal hearing and hearing impairment often results in poorer speech understanding for subjects with impairment (Ching, Dillon & Byrne, 1998; Hogan & Turner, 1998; Turner & Cummings, 1999). Studies also report that, in certain cases, providing audibility actually reduces the speech recognition abilities in subjects with sensorineural hearing impairment (Rankovic, 1991). The most widely applied model of speech recognition, the articulation index (AI) (French & Steinberg, 1947), is based upon the assumption that the contribution of a specific spectral region to speech recognition is determined solely by the audibility of that spectral region. However, speech-recognition deficits resulting from high-frequency hearing loss may not be limited to the loss of high-frequency speech information. Studies have shown that damage to the basal (i.e., high-frequency) region of the cochlea may be accompanied by changes such as reduced contributions from high-frequency auditory nerve fibers (Kiang & Moxon, 1974); reduced phase-locking and synchronization to low frequencies (Joris, Carney, Smith & Yin, 1994); disproportionate loss of activity from low-spontaneous-rate afferent fibers (Schmiedt, Mills & Boettcher, 1996) and efferent fibers (Liberman, Dodds & Pierce, 1990); reduced intensity discrimination (Florentine, 1983); and reduced temporal resolution (Jesteadt, Bacon & Lehman, 1982). Cochlear dead regions may add to the difficulty in understanding speech in quiet as well as in presence of noise.

There have been reports over a period of many years suggesting that people with moderate-to-severe hearing loss at high frequencies often do not benefit from amplification of high frequencies, or the performance deteriorates when high frequencies are amplified (Amos & Humes, 2001; Ching et al., 1998; Hogan & Turner, 1998; Turner & Cummings, 1999; Villchur, 1973). Recent investigations indicate that benefit derived from amplification depends on the presence or absence of dead regions (Vickers, Moore & Baer, 2001; Baer, Moore & Kluk, 2002; Vinay & Moore, 2007). Thus it is essential to assess for the presence or absence of dead regions to enable the clinician to provide appropriate amplification to individuals with sensorineural hearing loss.

Need for the study

The diagnosis of dead regions is clinically important as it determines the benefit derived from a hearing aid (Halpin, Thornton & Hasso, 1994; Vickers et al., 2001; Vinay & Moore, 2007a). A review of literature emphasizes that pure-tone audiometry does not directly reflect the presence of dead regions due to the phenomenon of off frequency listening (Patterson & Nimmo-Smith, 1980). Hearing loss will be infinite in the frequency of a dead region. In adults with acquired hearing losses, thresholds up to about 50 dB HL at low frequencies and 65 dB HL at high frequencies may be associated purely with outer hair cell dysfunction (Yates, 1990). It has been reported that losses greater than this degree tend to be associated with both outer hair cells and inner hair cells dysfunction, and losses greater than 90 dB HL at higher frequencies or 75–80 dB HL at lower frequencies are often associated with dead regions (Moore, Huss, Vickers, Glasberg & Alcántara, 2000; Moore, 2001). Due to the fact that the excitation pattern usually has a steep low frequency side, a dead region at higher frequencies is usually associated with a severe or profound hearing loss, and the audiogram pattern is often steeply sloping (Kapadia, Blakemore, Graumann & Phillips, 2002). However, dead regions do sometimes occur when the audiogram is not steeply sloping, and moderately steep slopes can occur in the absence of a dead region (Moore, 2001). Similarly in case of a low frequency dead region, there may not be a considerable amount of reduction in the hearing thresholds at low frequencies as the higher frequency neurons participate in response for the stimulus at low frequencies (Joris et al., 1994; Kiang & Moxon, 1974).

Attempts have been made to identify the presence or absence of dead regions based on the audiometric threshold (Aazh & Moore, 2007; Vinay & Moore, 2007a) and the results indicated that as the criterion hearing loss increased, the sensitivity decreased progressively while the specificity increased progressively. The criterion leading to the highest overall percent correct was 75 dB HL. However, for higher frequencies there was no threshold criterion having high sensitivity and high specificity. Hence, it has been argued that the presence or absence of dead regions cannot be determined reliably from the audiogram (Aazh & Moore, 2007; Halpin et al., 1994; Moore et al., 2000; Vinay & Moore, 2007a).

Studies have compared audiometric slopes in ears with and without dead regions and have concluded that subjects with dead region have higher slope values when compared to subjects without dead regions (Markessis, Kapadia, Munro & Moore, 2006; Preminger, Carpenter & Ziegler, 2005; Vinay and Moore, 2007a). However, these investigators have also observed an overlap in the slope values in subjects with and without dead regions (Preminger et al., 2005; Vinay & Moore, 2007a) and hence concluded that audiometric slope cannot be used to identify the presence of dead region. A majority of these studies have considered the slope inside the area of a dead region by taking the audiometric threshold difference between f_e and $2f_e$ in subjects with high frequency dead regions (Preminger et al., 2005; Vinay & Moore, 2007a). However, the estimation of slope outside the area of a dead region may provide important information regarding the prediction of a dead region. A study by Aazh and Moore (2007) considered slope values within and outside the area of the dead regions. However, the slope values were estimated only at 4000 Hz. Hence, the present study aims to estimate the slope based on the difference between the edge frequency and the adjacent octave as well as mid-octave frequency outside the area of the dead region for subjects with different edge frequencies.

Also, none of the studies have quantitatively examined the accuracy with which dead regions can be diagnosed based on combined criteria of audiometric threshold and slope of the audiogram. There is a need to investigate whether the combination of threshold and slope criteria will be more useful in predicting the presence or absence of a dead region.

An individual with normal hearing effectively utilizes the information from both the low and high frequencies essential for speech recognition. It has been reported that low frequencies play an important role in transmission of nasality and vowel cues (Wang, Reed, & Bilger 1978). Fricatives, affricates and some of the alveolar sounds have a higher formant frequency and thus the transition cues from a consonant to a vowel depend upon the transition frequency difference between a vowel and a consonant. Speech recognition will be affected selectively depending upon the region in the basilar membrane where the inner hair cells are lost. It has been observed that in listeners with normal hearing, speech recognition scores for filtered speech reduce, as the lowpass cut-off frequency is decreased (Wang et al., 1978). In a similar manner, the speech recognition scores may vary depending on the *fe* of the dead region. This is due to the fact that subjects with lower *fe* get limited information due to the presence of extensive dead region. There is a need to study the relationship between the speech recognition scores and the *fe* of a dead region to investigate the possibility of predicting speech identification scores based on the *fe* of dead region. Also, dead regions at different frequencies may differentially affect the perception of different consonants. Investigations have not been carried out to study the effect of *fe* of dead region on speech perception using error analysis. The error analysis helps to throw light on the effect of dead region at different frequencies on perception of different consonants.

There have been reports over a period of many years suggesting that people with moderate-to-severe hearing loss at high frequencies often do not benefit from amplification of high frequencies, or even perform more poorly when high frequencies are amplified (Amos & Humes, 2001; Ching et al., 1998; Hogan & Turner, 1998; Moore, Laurence, & Wright, 1985; Murray & Byrne, 1986; Turner & Cummings, 1999; Villchur, 1973). In these studies, no definite explanation was offered for the lack of benefit from amplification of high frequencies, although some investigators (Killion, 1997; Liberman & Dodds, 1984; van Tasell, 1993) speculated that inner hair cells or neural dysfunction might be involved. A major difficulty of listeners with hearing impairment in understanding speech arises from the loss of audibility of some parts of the speech signal that are important for recognition. Therefore, hearing aid amplification systems often aim to restore audibility of those portions of the speech spectrum that are below the listeners' thresholds. It is generally assumed that speech recognition will be optimized when audibility is maximized. However, research on the effect of audibility on speech recognition scores has demonstrated that audibility alone cannot adequately predict the reduced speech recognition of listeners with hearing impairment with moderate or severe losses (Ching et al., 1998; Dubno, Dirks & Ellison, 1989; Hogan & Turner, 1998; Kamm, Dirks & Bell, 1985; Moore, 2003; Pavlovic, 1984; Turner & Robb, 1987). This suggests that compensating for the loss of audibility may not always be helpful in individuals with hearing impairment.

It has been reported that those subjects who do not benefit from amplification have dead regions (or at least extensive damage to the inner hair cells) at high frequencies, while subjects who do benefit from amplification have surviving inner hair cells and neurons with high characteristic frequencies (Vickers et al., 2001). A majority of the studies have indicated that subjects with dead regions do not benefit from fullband amplification (Simpson, McDermott & Dowell, 2005; Vickers et al., 2001; Vinay & Moore, 2007b) but those with high frequency dead regions benefit from amplification up to one octave above the *fe* (Vickers et al., 2001). Also, the study done by Vestergaard (2003) found that low pass filtered speech produced significantly poor performance in subjects without dead regions. Subjects with dead regions obtained superior speech recognition scores. In a majority of these studies (Vickers et al., 2001; Vinay & Moore, 2007b), speech stimulus was amplified and then filtered using external filters. However, in real life situation, the signals that are heard through a hearing aid will be altered not only by the frequency but also by the other electroacoustic characteristics of the hearing aid. In one of the earlier studies (Mackersie et al., 2004), subjects used a digital hearing aid but the stimuli were filtered using an external filter. Results suggested that, in quiet and low levels of noise conditions, the unfiltered scores were better than the filtered scores. There was no difference between the scores of subjects with and without dead regions. In presence of high levels of noise, subjects without dead region performed significantly better than subjects with dead regions. However, the hearing aids that were used did not have adequate bands to provide individual gains at different frequencies. A digital hearing aid that can allow manipulation of gains at individual frequency bands may be more useful in providing amplification in subjects with dead regions. This would throw light on the actual benefit derived from amplifying different frequencies in a hearing aid in subjects with dead region.

Aims of the study: The present study was designed to investigate the following aims:

- Comparison of slope of the audiogram with the presence or absence of dead regions at different frequencies.
- Prediction of the presence or absence of dead regions based on audiogram in subjects with sensorineural hearing loss.
- Investigation and comparison of speech perception scores in subjects with or without dead regions.
- Investigation and comparison of speech perception scores in the following three different amplification conditions in subjects with high frequency dead regions:
    - i) Full band amplification
    - ii) Amplification up to the *fe* of the dead region
    - iii) Amplification up to one octave above the *fe*

CHAPTER II

REVIEW OF LITERATURE

Functioning of outer hair cells and inner hair cells is essential for normal hearing. Damage to either of these will lead to hearing loss of cochlear origin. Studies have shown that outer hair cells are more susceptible to damage than the inner hair cells (Liberman, Dodds & Learson, 1986) but hearing loss greater than 50 dB HL at low frequencies and up to 65 dB HL at high frequencies are generally associated with dysfunction of outer as well as inner hair cells. The degree of hearing loss varies depending on the extent of damage to inner hair cells. If the damage to inner hair cells is so extensive that they cannot respond to a signal, it is referred to as a dead region (Moore, 2001). A person with a dead region does not have any functional inner hair cells in that particular region. The characteristic frequency just adjacent to the dead region, at which there are surviving inner hair cells, defines the edge frequency (*fe)* of the dead region (Moore, 2001).

Identification of dead regions

Diagnosing the presence/absence and extent of a dead region is important for deciding on the appropriate form of amplification and for assessing candidacy for a cochlear implant (Baer, Moore & Kluk, 2002; Moore, 2004; Vickers, Moore & Baer, 2001). Pure tone audiometry does not directly reflect the presence of dead regions due to the phenomenon of off-frequency listening. The audiogram will give a misleading impression of the amount of hearing loss, for a tone whose frequency falls in the dead region (Gravendeel & Plomp 1960; Halpin, Thornton & Hasso, 1994). Effectively, the true hearing loss in a dead region is infinite, but the audiogram may sometimes indicate only a moderate degree hearing loss. This was shown by Halpin et al. (1994) in their study on subjects with low frequency hearing loss. They used the method of simultaneous pure-tone masking to assess the amount of apical damage associated with low frequency hearing loss. The performance-intensity function of speech recognition was measured and compared with the articulation index calculated based on the pure-tone audiogram. For this purpose, two audiograms were considered. One was the measured audiogram and the other was a hypothetical audiogram with 'infinite' hearing loss at low frequencies. The performance-intensity function calculated from the articulation index was determined separately for the two audiograms. In the first case, as the speech intensity was increased above 50 dB HL, the articulation index predicted speech intelligibility scores approaching 100%. In the case of the hypothetical audiogram, the predicted performance-intensity function did not increase once the speech level exceeded 70 dB HL. The results of two subjects were analyzed. In one of the subjects, the resulting speech performance prediction was 4% and it did not match the measured score (100%). The investigators concluded that, in this subject, the organ of corti survived in the apex and the performance-intensity curve is shifted by about 20 dB from the normal value. Whereas, in the other subject, the intelligibility predicted from the measured audiogram was 100 % for levels above 70 dB HL. The intelligibility predicted from the hypothetical audiogram was 7%. The latter matched the subject's word recognition performance. This indicates that the subject had low frequency dead regions with no functioning of inner hair cells/neurons in the apical part of the organ of corti.

Tests developed to detect the functioning of inner hair cells dates back to 1965. Langenbeck (1965), a proponent of ‘above threshold audiometry’ or ‘noise audiometry’, spectrally shaped a noise masker so that, for normal hearing listeners, it would produce equal masked thresholds for all the frequencies in the range from 125 Hz to approximately 8000 Hz. This test was used to differentiate auditory nerve damage from hair cell damage. He argued that if the threshold for detecting a tone in the presence of noise was much higher than normal, and was also above the absolute threshold, then this was indicative of nerve damage. The differences in function of the inner and outer hair cells were not known at this time. Also, the possibility that the spread of excitation to neurons whose characteristic frequencies were adjacent to the test signal was not considered (Moore, Huss, Vickers, Glasberg & Alcántara, 2000).

In the later years, research indicated that Psychoacoustic Tuning Curves (PTCs) can be used to detect and estimate the *fe* of a dead region (Florentine & Houtsma, 1983; Huss & Moore, 2003; Kluk & Moore, 2005; Moore et al., 2000; Moore & Alcántara, 2001). The measurement of PTCs involves a procedure that is analogous to physiological methods for determination of a tuning curve on the basilar membrane or a neural tuning curve (Chistovich, 1957). The method involves a signal of a fixed frequency presented at a fixed intensity, which is usually 10 dB above the absolute threshold. The masker can either be a tone or a narrow-band noise. Noise band is used as the masker rather than a sinusoid, to reduce the influence of beats (Egan & Hake, 1950; Moore & Glasberg, 1998). For different masker center frequencies, the level of the masker required just to mask the signal is determined. The frequency at which the least masker intensity is required to mask the signal determines the tip of the PTCs. The most effective masker has a frequency corresponding to the characteristic frequency of the place where the signal is detected (Moore & Alcántara, 2001). The drawback of the traditional PTCs method is that it is not time efficient.

Sek, Alcántara, Moore, Kluk and Wicher, (2005) developed a time efficient procedure that could assess the functioning of the inner hair cells. They devised a fast method for tracking the PTCs. The measurement method is similar to the principle used in Bekesy audiometry. In this method, the pure tone signal (Fs) will be pulsed to maintain the attention of the subject and will be presented at 10 dB SL. The method involves the use of narrow band noise masker that sweeps across frequencies from F_{min} to F_{max} for a forward sweep and F_{max} to F_{min} for a reverse sweep condition. The PTCs obtained from the fast method were compared with that of the traditional method. Results revealed very good agreement between the two methods (Sek et al., 2005). The fast method resulted in the tip of the PTCs being shifted away from the characteristic frequency in normal hearing subjects. The shift was found to be 2% above the characteristic frequency for the forward sweep condition and was 1% below the characteristic frequency for the reverse sweep condition. However, the shift in the tip of the PTCs was not significantly different from the tip obtained from the traditional method (Sek et al., 2005). The main disadvantage of the fast method PTCs is that it is still not available for clinical use. Hence a more efficient clinical tool to identify the presence of dead regions was developed by Moore et al. (2000).

Moore et al. (2000) developed a quick test for the identification of dead regions in the cochlea based on the method of 'above threshold audiometry', developed by Langenbeck (1965). The test is called Threshold Equalizing Noise (TEN) test as it requires the subject to detect a sinusoidal tone in the presence of "Threshold Equalizing Noise (TEN)". The spectral shape of the noise (P_s) is measured by using the formula, $P_s = N_o . K . ERB$, where N_o indicates noise spectral density, ERB is defined as the equivalent rectangular bandwidth of the auditory filter (Patterson & Moore, 1986) and K is the signal-to-noise ratio at the output of the auditory filter required to reach the threshold. Moore and Glasberg (1997) have estimated the value of K as a function of frequency and reported that the value of K decreases as frequency increases. The value of K at 1 kHz is about -3 dB, and it remains almost constant above 1 kHz. The ERB of a given filter is equal to the bandwidth of a perfect rectangular filter which has a transmission in its passband equal to the maximum transmission of the specified filter and transmits the same power of white noise as the specified filter (Moore, 1998). Glasberg and Moore (1990) showed that the value of the ERB could be estimated by the formula, $ERB = 24.7 (4.37F + 1)$, where the ERB is in Hertz and F is center frequency in kHz.

The repeatability of the TEN test has been investigated by Kiessling, Brenner, Ostergaard Olsen and Dyrlund, (2001) on subjects with sensorineural hearing impairment. They assessed the results of TEN test on 36 sensorineural hearing loss adults. The retest was done within two weeks of the original test. It was found that only six (55%) out of eleven subjects diagnosed as having dead regions gave the same test result on retest. Also, six (24%) of 25 subjects who did not meet the criteria for dead regions did meet the criteria on retest. The reason for this discrepancy may be due to the fact that the TEN test was administered in 5 dB steps in this study. This may lead to problems in diagnosis of dead regions, since there may be occasions when the masked threshold is exactly 10 dB above the noise level/ERB. In such cases the dead region may not be present had the test been done in 2 dB steps and the masked threshold being 8 dB above the noise level/ERB (Munro, Felthouse, Moore & Kapadia, 2005). Hence preferably a step size of 5 or 10 dB should be used to determine the approximate level corresponding to threshold, and then a smaller step size of 2 dB should be used to define the threshold more precisely (Moore, 2002; Moore, Glasberg & Stone, 2004).

The signal in the TEN test was calibrated in terms of hearing level (HL) and noise in sound pressure level (SPL) units. Moore, Glasberg and Stone, (2004) devised a newer version of the TEN test called the TEN (HL) in which both the signal and the noise are calibrated in HL units.

I.2. Prevalence of dead regions in subjects with sensorineural hearing loss

Studies have been carried out regarding the prevalence of dead regions in subjects with sensorineural hearing loss (Aazh & Moore, 2007; Markessis, Kapadia, Munro & Moore, 2006; Moore et al., 2000; Moore, Killen & Munro, 2003; Preminger, Carpenter & Ziegler, 2005; Vinay & Moore, 2007a). Moore et al. (2000) used the TEN (SPL) test and PTCs to assess 20 ears of 14 subjects with moderate to severe sensorineural hearing loss and with a variety of audiometric configurations. The age range of the subjects varied from 47 to 84 years. Sixty eight percent of their subjects met the criteria for a dead region. Moore, Killen and Munro (2003) assessed the prevalence of dead regions in teenagers with sensorineural hearing impairment. The mean age of the subjects was 14 years. The absolute and the masked thresholds in the TEN were established for each subject. Six ears of six different subjects had a dead region at low frequencies. Twenty-nine (46 %) ears did not meet the criteria for the presence of dead regions at any frequency. However, 23 (70%) subjects met the criteria for dead regions at medium to high frequencies in at least one ear. Five (15.2%) subjects had dead regions bilaterally, while the remaining 18 (54.5%) had dead regions in only one ear. Sixteen of the 24 subjects with a congenital hearing impairment, and four of the five subjects with an acquired impairment, met the criteria for a dead region. In most of these subjects, the diagnosis of the dead regions was inconclusive at some frequencies because the TEN could not be made sufficiently intense to produce significant masking effect.

Preminger et al. (2005) studied the prevalence of dead regions in 49 subjects for whom pure tone absolute thresholds for at least two frequencies were above 50 dB HL and no thresholds were above 80 dB HL. Markessis et al. (2006) considered a more broader range of hearing losses and assessed the prevalence of dead regions. They used the TEN (SPL) test to assess 35 adults (40 - 89 years old) with moderate to severe sloping sensorineural hearing loss. It was observed that, 87% of the ears met the criteria for a dead region for at least one test frequency. Absolute thresholds at 4 kHz were between 65 and 90 dB HL and 52 percent of 69 ears met the criteria for a dead region at 4 kHz.

Aazh and Moore (2007) considered 63 subjects (98 ears) with age range from 63 to 101 years. Subjects diagnosed as having sloping sensorineural hearing loss with an absolute threshold of 60-85 dB HL at 4000 Hz were considered for the study. They found that, of the 98 ears, 62 did not have a dead region at 4000 Hz and 36 did have a dead region. However, there have been only a few large scale studies assessing the prevalence of dead regions in subjects with sensorineural hearing loss. A study by Vinay and Moore (2007a) assessed the prevalence of dead regions on 317 (592 ears) subjects diagnosed as having sensorineural hearing losses that ranged to a wider degree from mild to severe compared to the previous studies (Markessis et al. 2006; Aazh and Moore, 2007). The TEN (HL) test was used to determine the presence or absence of dead regions for test frequencies ranging from 500 to 4000 Hz. It was found that 57% of the subjects were found to have a dead region in one or both ears for at least one frequency in which the TEN (HL) test was conclusive.

Thus the above studies indicate that a dead region is not a rare phenomenon. Many individuals with sensorineural hearing loss may be having dead regions. Hence there is a need to include tests for identifying dead regions in the audiological test battery.

I. 3. Prediction of dead regions based on audiometric slope / threshold

Studies have been carried out to predict the presence or absence of a dead region based on audiometric thresholds or slope values (Aazh & Moore, 2007; Moore et al., 2000; Vinay & Moore, 2007). Moore et al. (2000) suggested that dead regions at high frequencies are often associated with steeply sloping losses, and a high-frequency dead region can be present even at a frequency where the absolute threshold indicates only mild-to-moderate hearing loss. Hearing losses greater than 70 dB HL at high frequencies were often associated with a dead region, but some individuals with absolute thresholds of 70-80 dB HL had no dead region. Preminger et al. (2005) performed the TEN test using insert earphones. If at least one of the absolute thresholds was less than or equal to 60 dB HL, then the TEN level was set to 70 dB SPL/ERBN. If all absolute thresholds were 60 dB HL or higher, then the TEN level was set to the lowest threshold in quiet plus 10 dB. Ears for which the masked threshold was 15 dB above the absolute threshold and 15 dB above the TEN level were considered to have dead regions at the test frequency. Twenty nine percent of their subjects tested positive for dead regions. The slope of the audiogram was found to be significantly higher for ears with high-frequency dead regions (18.9 dB/octave) than for ears with no dead region (11 dB/octave). However, there was a considerable overlap between the audiogram slopes for subjects with and without dead regions. They concluded that the slope did not appear to be useful as a tool for predicting the presence or absence of a dead region.

A study by Aazh and Moore (2007) investigated if audiometric slope may be a reliable predictor for the presence of dead regions in subjects with sensorineural hearing impairment. They analyzed slope of the audiogram at 4000 Hz in subjects with sensorineural hearing loss with and without dead regions. The slope of audiogram in the frequency region above 4000 Hz was estimated as the difference in audiometric threshold between 4000 and 8000 Hz. The slope value for ears with and without dead regions was not statistically significant. The audiometric slope analyzed over the frequency region below 4000 Hz was estimated as the difference in audiometric threshold between 2000 and 4000 Hz. The difference in slope values between the two groups was not statistically significant. However, the mean audiometric threshold at 4000 Hz was significantly higher for the group with dead regions than for the group without dead regions. The study also assessed sensitivity and specificity values of audiometric thresholds in predicting the presence or absence of dead regions. Absolute threshold criteria of 60, 65, 70, 75, 80, and 85 dB HL were used. It was found that the sensitivity decreased progressively as the criterion hearing loss increased, while the specificity increased progressively. The criterion leading to the highest overall percent correct was 75 dB HL. However, with this criterion, only 47% of ears with dead regions were correctly diagnosed as having dead regions, while 18% of ears without dead regions were incorrectly diagnosed as having dead regions. Thus, accurate diagnosis of dead regions cannot be achieved using only the audiometric threshold at the test frequency.

It may be noted that Aazh and Moore (2007) considered audiometric data only at 4000 Hz. Investigation on subjects with sensorineural hearing loss having a wider range of degree of hearing loss was carried out by Vinay and Moore (2007a) who assessed whether audiometric findings can indicate the presence or absence of dead regions at all octave and mid-octave frequencies from 500 to 4000 Hz. They found that, for each test frequency, 59% or more of ears had a dead region when the absolute threshold was above 70 dB HL. It was observed that, as the threshold criterion was increased, sensitivity decreased but specificity increased. For frequencies up to 1500 Hz, the threshold criteria of 75 dB HL lead to sensitivity and specificity that were both above 81%. However, for higher frequencies there was no threshold criterion having high sensitivity and high specificity. This indicates that the presence or absence of a dead region cannot be predicted reliably from the absolute threshold at the test frequency. The slope of the audiogram was measured inside the area of a dead region between f_e and $2f_e$ for ears having high frequency dead regions and between $0.5f_e$ and f_e for subjects having low frequency dead regions. For the ears without dead regions, the slope of the audiogram increased with increasing frequency. For each value of f_e, the slope was greater for the ears with dead regions than for the ears without dead regions. However, there was a considerable overlap observed in the slope values between subjects with and without dead regions. It was found that, though a very steep audiometric slope was suggestive of a dead region, it did not provide a reliable diagnostic method.

A majority of these studies (Markessis et al., 2006; Preminger et al., 2005; Vinay & Moore, 2007a) have considered the slope inside the area of a dead region by taking the audiometric threshold difference between f_e and $2f_e$ in subjects with high frequency dead regions. However, estimation of the slope outside the area of a dead region may provide a different perspective regarding the prediction of a dead region. Also, previous studies have predicted the presence or absence of a dead region taking the audiometric threshold and slope criteria separately for each frequency. The combination of threshold and slope criteria may provide more information to predict the presence or absence of a dead region. Hence, investigations need to be carried out in this direction in order to know whether dead region can be predicted based upon audiometric findings.

I.4. Speech perception and dead regions

Studies report that subjects with sensorineural hearing loss have reduced speech recognition abilities (Hogan & Turner, 1998, Turner & Cummings, 1999) and these problems are further compounded by the presence of dead regions (Vickers et al., 2001). There are several reasons responsible for subjects with dead regions extract little or no information from frequency components of speech that fall within a dead region, even when those components are amplified sufficiently to make them audible

(Moore, 2001). The studies reviewed below provide a view of the speech recognition abilities in sensorineural hearing loss subjects with and without dead regions.

I.4.1. Speech recognition abilities in sensorineural hearing loss subjects without dead regions

A review of literature suggests that the presence of sensorineural hearing impairment may reduce the contribution of speech information in a given frequency region to speech understanding (Pavlovic, Studebaker, & Sherbecoe, 1986; Studebaker, Sherbecoe, McDaniel & Gray, 1997). It has been reported that the presence of hearing impairment results in a uniform deficit in the contribution of speech information across all affected frequencies (Boothroyd, 1978; Pavlovic, 1984; Pavlovic et al., 1986; Schuchman, Valente, Beck & Potts, 1999; Studebaker et al., 1997). Individuals with sensorineural hearing loss often complain of difficulty with speech understanding. The extent and nature of the difficulty depends partly on the severity of the hearing loss. Subjects with mild or moderate degree can usually understand speech reasonably well in quiet or noisy situations. However, subjects with severe or profound degree usually have difficulty even when understanding speech in quiet condition. There has been considerable controversy in literature about the speech recognition abilities in subjects with sensorineural hearing loss. Some studies have concluded that the difficulties arise primarily due to reduced audibility to discriminate speech sounds (Dreschler & Plomp, 1980; Humes, Dirks, Bell & Kincaid, 1987; Plomp, 1978; Zurek & Delhorne, 1987).

The processes used for identification and discrimination of consonants were investigated by Reed (1975) in eight persons with sensorineural hearing loss and three subjects with normal hearing. In the identification task a feature analysis of transmitted information for VC syllables was used to study encoding ability. In individuals with hearing loss, the transmitted information was reduced when compared to that of subjects with normal hearing, indicating a loss of ability to encode consonants. In the discrimination task, coding ability was studied by measuring reaction times for ‘same’ and ‘different’ decisions. The reaction times for individuals with impaired hearing were found to be significantly different from those subjects with normal hearing. Thus, the results indicate that the two groups of subjects use different processing modes in discriminating between pairs of phonemes. This may result in altered perception in subjects with hearing impairment.

The effect of degree of hearing loss and age on discrimination scores was studied among listeners with flat sensorineural hearing losses by Bess and Townsend (1977). The results showed that the average subject exhibited a discriminative ability of 70% or better for hearing levels less than 60 dB HL. A 10 to 20% decline in intelligibility was found for losses 60 dB HL and greater. Listeners' performance decreased as a function of age especially for subjects with the greatest hearing losses. These results suggest that audibility may be a factor affecting speech understanding when the degree of hearing loss is greater than 60 dB HL Posner and Ventry (1977) investigated the relationship between the sensation level selected as most comfortable for loudness and intelligibility, and the sensation level at which maximum speech discrimination is obtained. An articulation function was generated at five sensation levels for 45 subjects with sensorineural hearing loss. Speech discrimination scores were also obtained at sensation levels corresponding to most comfortable loudness levels for loudness and intelligibility.

Results indicated that most comfortable loudness did not appear to be the level at which maximum speech discrimination was obtained.

To investigate the importance of different frequencies in perception of speech in subjects with hearing impairment, studies were carried out by filtering speech stimuli and analyzing the speech recognition abilities in subjects with sensorineural hearing loss. Franklin (1975) made comparison of the effect on consonant-recognition scores when a low-frequency passband and a high-frequency passband were presented to subjects with hearing-impairment. The Fairbanks Rhyme Test was filtered into two bands- 240-480 Hz (low band) and 1020-2040 Hz (high band). The high band was presented at 10 dB above threshold at 1500 Hz to the better ear of six subjects with moderate to severe sensorineural hearing losses. When the low band and high band were added to the same ear, there was little change in the consonant-recognition score at each of the three sensation levels. This may be because filtering the very low frequencies from 240 to 480 Hz does not interfere with the speech recognition abilities in these subjects. This indicates that very low frequency cues may not be essential for speech perception. Studies have been carried out using a much broader pass bands than used in this study. Boothroyd (1978) measured speech understanding under various conditions of low and high pass filtering to determine the relative contribution of different frequency regions to phoneme identification for children with different configurations of hearing loss. Results showed that for persons with flat frequency hearing losses the contribution of speech information was reduced across all frequencies equally and individuals with high frequency hearing losses showed a reduced contribution of speech information primarily in the regions where hearing loss was present and followed the normal pattern in regions where hearing was near normal. It was observed that it was primarily the presence of hearing loss that resulted in a reduction in the contribution of a frequency region to speech understanding, regardless of the frequency region where the loss occurred. It can be inferred from this study that the speech perception abilities vary depending on the configuration of hearing loss.

A study by Wang, Reed and Bilger (1978) determined whether normal listeners, presented with filtered speech, would perceive speech similar to those previously reported for the listener with hearing impairment. Consonant confusion matrices were obtained from eight normal-hearing subjects for four sets of CV and VC nonsense syllables presented under six high-pass and six-low pass filtering conditions. Patterns of consonant confusion for each condition were described using phonological features in sequential information analysis. It was observed that severe low-pass filtering produced consonant confusions comparable to those of listeners with high-frequency hearing loss. Severe high-pass filtering resulted in comparable scores to that of patients with flat or rising audiograms. It was observed that mild filtering resulted in confusion patterns comparable to those of listeners with essentially normal hearing. Hence filtering of speech sounds may have adverse effects on the consonant perception abilities in subjects with sensorineural hearing loss. However, the effect of filtering the frequencies may be investigated in a more realistic way by considering subjects with sloping hearing losses who do not obtain important high frequency cues responsible for speech perception.

Studies have been carried out to know the effect of audiometric configuration on speech recognition abilities in subjects with sensorineural hearing loss. It has been found that listeners with sensorineural hearing loss who show similar patterns of consonant confusions also tend to have similar audiometric profiles. Walden and Montgomery (1975) analyzed consonant perception in subjects who had normal hearing, high-frequency sensorineural hearing loss, or relatively flat sensorineural hearing loss. The subjects had to rate similarity between consonants that were presented. The individual differences were modeled through a program that uses multidimensional analysis called as Individual Difference Scaling (INDSCAL) to derive a set of perceptual features empirically from the similarity judgments, and to group the subjects on the basis of strength of feature usage. The analysis revealed that sonorance was the dominant dimension in the similarity judgments of the subjects with high-frequency hearing losses, while sibilance tended to dominate the judgments of the subjects with flat audiometric configurations. The normal-hearing subjects tended to weigh these two dimensions approximately equally. These differences in similarity judgments were observed based upon audiometric configuration, despite the fact that the two groups with hearing-impairment were not unique in word-recognition ability. These results suggest that cues for consonant perception differ according to the configuration of hearing loss.

The effects of audiometric configuration on perception of different features of consonants were investigated by Gutnick (1982), who analyzed normal-hearing listeners and listeners with a high-frequency sensorineural hearing loss on identification of 17 consonants as part of a consonant-vowel syllable with /a/ or /i/ as the vowel. The syllables were set at presentation levels of 10 to 65 dB re thresholds at 1000 Hz. The performance of the listeners with hearing-impairment was significantly poorer than the performance of the normal-hearing listeners only for the higher-frequency features of frication and sibilance. The lower-frequency features of voicing and sonorance were reflected in the confusion matrices of listeners with hearing-impairment at presentation levels of 10 and 20 dB whereas higher-frequency features were transmitted only at 35 to 65 dB.

Dubno, Dirks and Langhofer (1982) assessed syllable recognition ability and consonant confusion patterns for 38 subjects with mild-to-moderate sensorineural hearing loss. Consonant recognition scores for subjects with steeply sloping audiometric configurations were consistently poorer than those for listeners with gradually sloping or flat audiograms. Consonant confusion analyses revealed place of articulation errors to be the most frequent, regardless of the listener's audiometric configuration. Analysis of consonant confusion patterns indicated the existence of a systematic relationship between consonant confusions and audiometric configuration.

Though research indicates that audiometric configuration is one of the main factors affecting speech recognition scores, studies indicate that other factors such as frequency resolution will also affect the speech recognition scores. Festen and Plomp (1983) reported that speech recognition ability in quiet in subjects with hearing impairment mainly depended on audiometric thresholds whereas speech recognition in noise was affected mainly by the frequency resolution. Preminger and Wiley (1985) investigated the relation between frequency selectivity and consonant intelligibility in subjects with sensorineural hearing loss. Three matched pairs of subjects with similar audiometric configurations (high-frequency, flat or low-frequency hearing loss) but significantly different word-intelligibility scores were tested. Characteristics of psychophysical tuning curves (PTCs) for high- and low-frequency probes were compared with speech-intelligibility performance for high- and low-frequency consonant-vowel syllables. Frequency-specific relations between PTC characteristics and consonant-intelligibility performance were observed in the subject pairs with high frequency and flat sensorineural hearing loss. Corresponding results for the subject pair with low-frequency sensorineural hearing loss were equivocal.

Studies have reported that poor speech-understanding performance of some of the elderly listeners, especially for complex signals, may be associated with other factors related to disproportionate deficits in temporal resolution and frequency resolution. Dubno, Dirks and Schaefer (1989) used Articulation index (AI) theory to evaluate stop-consonant recognition of normal-hearing listeners and listeners with high-frequency hearing loss. A transfer function relating the AI to stop-consonant recognition was established, and a frequency importance function was determined for the nine stop-consonant-vowel syllables used as test stimuli. The AI model was then used to predict performance for the listeners with hearing impairment. A majority of the AI predictions for the subjects with hearing impairment fell within +/- 2 standard deviations of the normal-hearing listeners' results. However, the AI tended to overestimate performance of the listeners with hearing-impairment. The accuracy of the predictions decreased with the magnitude of high-frequency hearing loss. This shows that factors other than audibility were responsible for .reduced speech recognition scores in these individuals.

Studies carried out by simulating hearing loss in subjects with normal hearing using masking paradigms have also revealed similar results. Dubno and Ahlstrom (1995) assessed consonant recognition in six low-pass maskers as a function of masker bandwidth for subjects with hearing impairment and for normal-hearing subjects listening in spectrally shaped broadband noise (SSBB). SSBB was adjusted such that thresholds in that masker for a normal-hearing listener were equal to the absolute threshold of listeners with hearing impairment. Slopes of functions relating consonant recognition to speech level were not significantly different between groups, due to the presence of SSBB for the normal-hearing listeners. However, 25% of observed scores for listeners with hearing impairment, compared to only 5% of observed scores for normal-hearing listeners, were significantly poorer than predicted by the articulation index (AI), when AIs were computed using subjects' absolute thresholds. Better correspondence between observed and predicted scores in low-pass maskers was achieved when AIs were derived empirically from thresholds measured in each low-pass masker. Hence poor predicted consonant recognition scores in low-pass maskers were accounted for higher thresholds in those maskers.

Similarly, a study by Phillips, Gordon-Salant, Fitzgibbons and Yeni-Komshian (2000) assessed temporal resolution, as measured by gap detection, and frequency resolution, as measured by the critical ratio, were examined in older listeners with normal hearing, older listeners with hearing loss and good speech-recognition performance, and older listeners with hearing loss and poor speech-recognition performance. Listener performance was evaluated for simple and complex stimuli and for tasks of added complexity. In addition, syllable recognition was assessed in quiet and noise. The principal findings were that older listeners with hearing loss and poor word-recognition performance did not perform differently from older listeners with hearing loss and good word recognition on the temporal resolution measures nor on the spectral resolution measures for relatively simple stimuli. However, frequency resolution was compromised for listeners with poor word-recognition abilities when targets were presented in the context of complex signals. Thus, the findings support the hypothesis that unusual deficits in word-recognition performance among elderly listeners were associated with poor spectral resolution for complex signals.

Studies have been carried out to know the benefits of amplification in subjects with sensorineural hearing loss having different degrees. Murray and Byrne (1986) conducted studies on speech recognition abilities in subjects with high frequency sensorineural hearing. The stimuli were low-pass filtered with cut-off frequencies of 1.5, 2.5, 3.5 and 4.5 kHz. There was an additional filter that provided a high-pass cut-off at 170 Hz. Speech signals were presented in presence of speech-shaped noise. Results indicated that amplification at higher frequencies was not beneficial for subjects with moderate-to-severe high frequency hearing losses.

Gordon-Salant (1984) assessed the effect of low-frequency amplification on speech recognition performance by listeners with hearing impairment. Consonant identification performance by subjects with flat hearing losses and high-frequency hearing losses was assessed in different hearing aid conditions. The experimental hearing aids all provided extra high-frequency amplification but differed in the amount of low-frequency amplification. The results showed that listeners with flat hearing losses benefited by low-frequency amplification, whereas subjects with high-frequency hearing losses exhibited deteriorating scores in conditions with greatest low-frequency amplification. This shows that audiometric configuration may play an important role in obtaining benefit from amplification in subjects with sensorineural hearing loss. Further studies were carried out by Gordon-Salant (1987) to investigate the aided consonant recognition and confusion patterns associated with hearing loss among elderly listeners.

Subjects were all greater than 65 years, and had normal hearing, or gradually or sharply sloping sensorineural hearing losses. Recognition of 19 consonants, paired with each of three vowels in a CV format, was assessed at two speech levels in a background of babble (+6 dB signal-to-babble ratio). Analyses of percent correct scores for overall nonsense syllable performance and for consonants according to place, manner, and voicing categories generally revealed better performance by the normal-hearing subjects than by the subjects with hearing impairment. However, individual differences scaling analysis of consonant confusions failed to retrieve speech perception patterns that were unique to listener group. Hence this study shows that perception of consonants differs according to the configuration of hearing loss.

Hogan and Turner (1998) described the efficiency with which persons with high-frequency sloping sensorineural hearing impairment were able to make use of speech information in various frequency regions. They studied subjects who had normal hearing at lower frequencies and losses from 40 to 110 dB HL at higher frequencies. Subjects were required to identify nonsense syllables presented after filtering. They found that the subjects were limited in their ability to make use of amplified speech information above 4000 Hz, particularly when the degree of hearing loss in this frequency region exceeded about 50 dB HL. These subjects were better in utilizing the low frequency information even in the presence of a similar degree of hearing impairment. Comparison of performance for speech stimuli passed through filters with different cut-off frequencies showed that increasing the high-frequency cut-off had little or no benefit on speech recognition scores in these subjects. An investigation by Turner and Cummings (1999) supports these findings. They tested 5 subjects with normal hearing and 11 subjects who had high-frequency hearing losses. Subjects listened to unfiltered nonsense syllables in quiet as presentation levels were systematically increased until asymptotic performance levels were reached. The results, combined with calculations of audibility, indicated that providing audibility above 3000 Hz was not beneficial in improving their speech recognition to subjects with high-frequency hearing impairment greater than about 55 dB HL. Ching, Dillon and Byrne, (1998, 2001) also reported similar findings on speech recognition performance of subjects with sensorineural hearing impairment using filtered sentence materials in quiet. Probably subjects in these studies had dead regions at high frequencies because of which amplification was of limited use.

Sammeth, Tetzeli and Ochs (1996) assessed consonant recognition performance in 18 subjects with sensorineural hearing loss listening in quiet and speech noise with linear and nonlinear hearing aids. Subjects were divided into three groups by audiometric configuration: flat, moderately sloping, and sharply sloping. Consonant-to-vowel ratios (CVRs) were calculated for syllables processed through each hearing aid. It was observed that intersubject variability in performance was high, even within subjects having similar configuration. High-frequency phonemes were more often audible with the nonlinear than with the other hearing aids for subjects with moderately and severely sloping audiograms. Scores increased for some phonemes with a nonlinear hearing aid versus linear suggesting that sensorineural hearing loss subjects benefit more from compression circuits than the linear circuits.

Souza and Bishop (2000) determined whether increases in audibility with nonlinear amplification improved speech recognition to a comparable degree for subjects with sloping sensorineural loss compared to subjects with flat sensorineural loss.

Consonant recognition was examined as a function of audibility with wide dynamic range compression amplification and with linear amplification. For linear amplification, listeners with flat and sloping loss showed similar improvements in speech recognition given the same increases in audibility. Results for nonlinearly amplified speech indicated that the subjects with flat loss showed a greater rate of improvement as audibility increases than the subjects with sloping loss. The difference may be due to superior performance by the subjects with sloping loss for low-audibility speech in comparison to equivalent group performance for high-audibility speech.

Contrary to the performance in quiet, studies indicate that speech recognition scores in the presence of noise improve when amplification is provided at high frequencies. Turner and Henry (2002) suggested that the presence of background noise may play an important role in determining the benefits of amplified high frequency speech information. They measured the efficiency with which subjects with sloping sensorineural hearing impairment could make use of increases in high-frequency speech information. Speech understanding was measured at different low pass cut-off frequencies in a multi-talker babble noise. In contrast to the studies carried out in quiet, subjects with high frequency hearing loss were able to use amplified high frequency speech information to improve speech understanding regardless of the degree of hearing impairment.

Hornsby and Ricketts (2003) studied speech recognition abilities in 27 subjects, 9 with sensorineural hearing impairment and 18 with normal hearing. Sentence recognition was assessed using the connected speech test (Cox, Alexander & Gilmore, 1987; Cox, Alexander, Gilmore & Pusakulich, 1988). Speech recognition abilities were assessed in noise using different low and high pass filter cut-off frequencies. Noise levels were chosen to ensure that the noise, rather than the quiet thresholds, determined audibility. The performance of the subjects with hearing impairment was compared to a normal hearing group at the same signal-to-noise ratio and a comparable presentation level. Although aided speech recognition scores for the group with hearing impairment were reduced, performance improved as the speech and the noise bandwidth increased. The study concluded that high frequency information (above 3000 Hz) could be useful in speech recognition for subjects with sensorineural hearing loss. Also, when hearing losses across frequencies is similar for subjects with flat frequency hearing impairment, the relative importance of each frequency region appears to be similar to that of subjects with normal hearing. It was found that subjects with sensorineural hearing impairment could have a significant deterioration in speech recognition abilities even in the absence of dead regions.

Amos and Humes (2007) investigated the contribution of audible high-frequency information to speech-understanding performance in listeners with varying degrees of high frequency sensorineural hearing loss. Thirty-six listeners with hearing impairment and 24 listeners with normal hearing were tested in quiet (+20 dB speech-to-noise ratio [SNR]) and noise (+5 dB SNR) and under different bandpass conditions (narrow, 200-1600 Hz; midband, 200-3200 Hz; broadband, 200-6400 Hz), both without and with spectral shaping of the stimuli. Monosyllabic word-recognition performance was examined through use of both whole-word scoring and phoneme scoring. Results for spectrally shaped speech, in both quiet and noise, revealed that the groups with hearing impairment performed equivalently in the different bandwidth conditions and demonstrated no change (increase or decrease) in word-recognition performance between the midband and broadband conditions. The normal hearing groups, however, demonstrated improved speech understanding attributable to the higher frequencies for the broadband condition in both the unshaped and shaped conditions. It was observed that, for the group with hearing impairment, 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.

Thus, a review of literature indicates that though hearing aids are the primary method for alleviating problems associated with sensorineural hearing loss, some of the subjects do not benefit from high frequency amplification. The presence or absence of dead regions was not assessed in these studies. It is possible that the subjects who did not benefit from amplification had high frequency dead regions.

I.4.2 Speech recognition abilities in sensorineural hearing loss subjects with dead regions

Subsequent to the development of tests to identify dead regions, attempts have been made to investigate the speech recognition abilities with and without amplification in individuals identified to have dead regions and compare the results with those obtained without dead regions. Vickers et al. (2001) investigated the benefits from amplification in subjects with and without high frequency dead regions. The presence or absence of dead region was tested using both psychophysical tuning curves and the threshold equalizing noise (TEN) test (Moore et al., 2000) in 10 subjects with high frequency hearing loss. They compared the speech understanding in quiet of two groups of subjects with hearing impairment at different low pass cut-off frequencies. One group of subjects had high frequency dead regions while the other group did not. Subjects were tested for speech recognition performance using vowel-consonant-vowel (VCV) nonsense syllables. The stimuli were subjected to the frequency-gain characteristics recommended by the Cambridge formula (Moore & Glasberg, 1998). The task of the subjects was to recognize the consonants in the VCV list. For subjects with hearing impairment without dead regions, the scores improved as the cut-off frequency increased which indicated that these subjects could utilize information from higher frequencies for speech recognition. For subjects who had dead regions, performance improved as the cut-off frequency was increased up to about one octave above the estimated *fe* of the dead region. Providing high frequency amplification one octave above the estimated *fe* of the dead region had deteriorating effect or there was no improvement in the speech recognition scores. In general, individuals with high frequency dead regions made limited use of amplified high frequency information to improve speech understanding. In contrast, subjects with hearing impairment but without dead regions showed consistent improvement in speech understanding as low pass cut-off frequency was progressively increased. These results indicate that the frequency response of the hearing aid should be set based on the *fe* of the dead region. Baer et al. (2002) observed a pattern similar to Vickers et al. (2001) for subjects with and without high frequency dead regions listening to nonsense syllables at different lowpass cut-off frequencies in a noisy background.

Similar results were obtained by Vinay and Moore (2002) in a subject with low frequency dead region. Normal hearing and sensorineural hearing loss subjects without dead regions served as the control group. The identification of dead regions was done using the TEN test. Twenty-one consonants in VCV context were presented as stimuli. The speech recognition scores were found in these subjects in quiet condition. The audiograms of the subjects were fed into the Cambridge formula and the required gain was estimated for each frequency in order to provide amplification to speech stimuli. Five different highpass cut-off frequencies, 353, 707, 1414, 2828 and 5656 Hz were used. Stimuli were presented to the subject through the headphones and speech recognition scores were obtained for unfiltered and five sets of filtered condition. Subjects with normal hearing and sensorineural hearing loss without dead regions obtained good scores in the unfiltered condition. There was deterioration in the speech recognition scores in the subject with low frequency dead regions when amplification was provided 1-1.5 octaves below the *fe* of the dead region. It was observed that the speech recognition scores were maximum when amplification was provided up to one octave below the *fe* of low frequency dead region. Thus selective amplification may be beneficial in sensorineural hearing loss subjects with dead regions.

Simpson, McDermott and Dowell (2005) carried out consonant identification task with 10 subjects with hearing-impairment under various low-pass filter conditions. Subjects were also tested for cochlear dead regions with the TEN test. All the subjects had moderate-to-severe high-frequency hearing losses. Consonant recognition was tested under conditions in which the speech signals were highly audible to subjects for frequencies up to the low-pass filter cut-off. It was found that only one subject had extensive dead regions. They report that the remaining subjects had dead regions above 3000 Hz, as indicated by the severity of the hearing losses, but could not be demonstrated with the TEN test. Consonant scores improved significantly ($p<0.05$) with increasing audibility of high-frequency components of the speech signal for subjects without extensive dead regions. Nine of the subjects showed improvements in scores with increasing audibility, whereas the remaining subject showed little change in scores. For this subject, speech perception results were consistent with the TEN test findings for the presence of extensive dead regions having a lower fe. In general, the results suggest that subjects with severe high-frequency losses without extensive dead regions such as having fe at or above 3000 Hz are often able to make some use of high frequency speech cues if these cues can be made audible.

Vinay and Moore (2007b) measured speech recognition abilities in quiet at various highpass cut-off frequencies in subjects with and without low frequency dead regions. Twenty-eight subjects diagnosed as having sensorineural hearing loss was considered for the study. The diagnosis of dead regions was based on the results of TEN test and the PTCs were established for more accurate estimation of f_e. The speech stimuli were vowel-consonant-vowel (VCV) nonsense syllables. Twenty-one consonants in VCV context were presented as stimuli. Prior to presentation via earphones, the stimuli were subjected to the frequency-dependent amplification prescribed by the “Cambridge” formula (Moore & Glasberg, 1998). Subjects were tested using broadband speech (upper frequency limit 7500 Hz) and speech that was highpass filtered with various cutoff frequencies. Results showed that the speech recognition abilities improved as the highpass cut-off frequency increased from 100 Hz up to about $0.57f_e$ and further increases in the cut-off frequency resulted in decrease in the speech recognition scores. However, for subjects with low-frequency hearing loss but without dead regions, scores were high (about 78%) for low cutoff frequencies, remained approximately constant for cutoff frequencies up to 862 Hz, and then worsened with increasing cutoff frequency. Thus it was concluded that subjects with low frequency dead regions do not benefit or the scores deteriorate by providing amplification below $0.57f_e$.

However, some studies have reported that subjects with dead regions showed superior speech recognition abilities under conditions of poor audibility, compared to subjects without dead regions (Mackersie, Crocker & Davis, 2004; Vestergaard, 2003). Vestergaard (2003) assessed speech recognition performance in sensorineural hearing loss subjects with and without dead regions. TEN test was used to identify the presence of dead regions. Low pass filtered speech was presented as stimuli through the subjects' own hearing aids. Speech recognition abilities were compared in subjects with and without dead regions at high frequencies. It was found the low pass filtered speech produced significantly poor performance in subjects without dead regions. Subjects with dead regions obtained superior speech recognition scores. This showed that subjects with dead regions exhibited smaller individual variation from group recognition prediction performance, and, subjects with dead regions showed superior speech recognition abilities under conditions of poor audibility, compared to subjects without dead regions. However, the low pass filter conditions used in this study were based upon the hearing aid fitting. This may have contributed to the difference in the results in these groups of subjects.

The results of a study carried out by Mackersie et al. (2004) contradict earlier reports (Vickers et al., 2001; Vinay & Moore, 2002;). Mackersie et al. (2004) compared threshold matched subjects with and without dead regions. Speech perception scores were measured in quiet and in different signal to noise conditions. Consonant identification task was carried out in quiet condition. Computer-Assisted Speech Perception Assessment test (CASPA) was carried out to measure the phoneme recognition at signal to noise ratios ranging from 0 to +15 dB. Recognition scores were obtained for unfiltered stimuli and stimuli that were low pass filtered half and one octave above the estimated *fe* of the dead region. Results suggested that, in quiet and low levels of noise conditions, the unfiltered scores were better than the filtered scores. There was no difference in the scores between subjects with and without dead regions. In presence of high levels of noise, subjects without dead region performed significantly better than subjects with dead regions. These differences in the results could be due to the fact that these subjects had a lesser degree of hearing loss and a higher boundary of the *fe* compared to the earlier studies (Mackersie et al., 2004).

The deterioration in the speech recognition abilities in subjects with dead regions may be due to the fact that these subjects have altered pitch perception. Studies investigating pitch perception in subjects with low-frequency dead regions report that a tone with a frequency falling in a dead region is often perceived with a low pitch that is roughly normal (Florentine & Houtsma, 1983). The detection of the tone that is falling in a dead region will be perceived by neurones that are farther away from the characteristic frequency that has surviving inner hair cells. Thai-Van, Micheyl, Norena and Collet, (2002) suggested that the slope of the hearing loss near the *fe* was the most important factor for the occurrence of local improvements in difference limen in frequency in subjects with dead regions. Huss and Moore (2005a) studied the perception of pure tones in subjects with low or high frequency dead regions. It was found that perception of tones in these subjects occurs mainly through the phenomenon of off-frequency listening. The variability in the pitch perception was more when the tone falls well within the dead region. The pitch matches within the same ear for tones that fall 0.5 octaves within the low or the high frequency dead region did not evoke a clear pitch sensation. For the pitch matches across the ears having asymmetric hearing losses and for pitch matching within ears indicated that the tones falling within a dead region was perceived in a different pitch than normal (Huss & Moore, 2005a).

Huss and Moore (2005b) studied subjects with hearing impairment who report pure tones as sounding highly distorted. It was observed that the noisiness rating was on average higher for the subjects with hearing impairment than for the normal hearing subjects. For subjects with hearing impairment, the ratings were not markedly different for tones with frequencies just outside or inside a dead region. The results indicated that the judgment of a tone as sounding noise-like might be the possible reason for reduced speech recognition abilities in subjects with dead regions.

In a majority of the studies (Vickers et al., 2001; Vinay & Moore, 2007b), speech stimulus was amplified and then filtered using external filters. In real life situation, the signals that are heard through a hearing aid will be altered not only by the frequency but also by the other electroacoustic characteristics of the hearing aid. As a result, the benefit derived from amplification may be different from that reported in these studies. Also, it may be observed that the study done by Vestergaard (2003) found that low pass filtered speech produced significantly poor performance in subjects without dead regions. Subjects with dead regions obtained superior speech recognition scores. This showed that subjects with dead regions exhibited smaller individual variation from group recognition prediction performance, and, subjects with dead regions showed superior speech recognition abilities under conditions of poor audibility, compared to subjects without dead regions. However, the hearing aids that were used did not have adequate bands to provide individual gains at different frequencies. Hence, a digital hearing aid that can allow manipulation of gains at individual frequency bands should be used to assess the speech recognition performance in subjects with dead regions. It would be more realistic, if the frequency response of a hearing aid can be altered to simulate different filtered speech conditions. This would throw light on the actual benefit derived from amplifying different frequencies in a hearing aid in subjects with dead region.

In one of the earlier studies (Mackersie et al., 2004), subjects used a digital hearing aid but the stimuli were filtered using an external filter. Results suggested that, in quiet and low levels of noise conditions, the unfiltered scores were better than the filtered scores. There was no difference in the scores between subjects with and without dead regions. In presence of high levels of noise, subjects without dead region performed significantly better than subjects with dead regions. These differences in the results could be due to the fact that these subjects had a lesser degree of hearing loss and a higher boundary of the *fe* compared to the earlier studies. Thus, there are equivocal findings regarding benefits of amplification from a hearing aid in subjects with dead regions.

CHAPTER III

METHOD

Participants

The study consisted of 208 participants (372 ears; 74 females and 134 males) diagnosed as having sensorineural hearing impairment. The age range of the participants varied from 30 to 79 years (Mean age=56.76; SD=14.44). The participants were divided into two age groups: Group I consisted of individuals in the age range of 30 to 59 years (Mean age=45.26; SD=9.06) and Group II included participants in the age range of 60 to 79 years (Mean age=69.77; SD=5.5). The degree of the hearing loss varied from minimal to profound. The participants were native speakers of Kannada language with no significant history of any speech and language disorder. All the participants reported that they had acquired hearing loss after the acquisition of speech and language.

Instrumentation

The following instruments were used in the present study:

i) Madsen OB922 dual channel clinical audiometer consisting of TDH-39 headphones with MX-41/AR supra-aural earcushions, and sound field speakers. The audiometer was calibrated to confirm to ISO 389-8 (2004) standards.

ii) Grason-Stadler TympStar middle ear analyzer calibrated according to ANSI (1987) standards.

iii) A computer

iv) Philips 729K Compact Disc player

v) A 16 channel digital hearing aid with fitting range for participants with minimal to profound hearing loss.

Material

The following materials were used in the present study:

i) Threshold Equalizing Noise (calibrated in dB HL) test compact disc (Moore, Glasberg & Stone, 2004).

ii) The word lists from the Speech Identification Test in Kannada developed by Vandana (1998). The word list is given in Appendix A.

iii) A Consonant-vowel (CV) list consisting of 21 consonants. The consonants were /k, g, tʃ, dʒ, ṭ, ḍ, ṇ, t, d, n, p, b, m, j, r, l, v, ʃ, s, h, ḷ /. Vowel in the CV context was /a/. Ten randomized lists were prepared. The CV list is given in Appendix B.

Preparation of the material

A computer with Audio Lab software (32 Bit, Mono, 44100 Hz, 63 KB/S) was used to record the speech stimuli. Speech material was recorded using a male voice in a sound treated room by a native Kannada speaker using a Sony microphone D-500 at a distance of 15cm from the lips of the speaker. The recorded stimuli were scaled to maintain equal intensity. Goodness test for the recorded material was carried out by presenting the stimuli to 10 individuals with normal hearing. All the normal hearing participants obtained 100% score indicating that speech material was highly intelligible.

Procedure

All the evaluations were done in an acoustically treated room where the ambient noise levels were within permissible limits (ANSI, 1999).

Pure tone audiometry

Air conduction thresholds were determined at the octave/mid-octave frequencies, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz and bone conduction thresholds were determined at 250, 500, 1000, 2000 and 4000 Hz for all the participants. The thresholds were measured using the modified Hughson-Westlake procedure proposed by Carhart and Jerger (1959).

Immittance evaluation

Tympanometry and reflexometry was carried out on all the participants using a Grason-Stadler TympStar middle ear analyzer to rule out the presence of middle ear pathology.

TEN (HL) test

After the initial diagnosis of sensorineural hearing loss, the participants were administered the TEN (HL) test to identify the presence or absence of dead regions. The test involves detection of signal in the presence of TEN. The CD of TEN (HL) test was played via a Philips 729K CD player and stimuli were presented to the same ear through the headphones of the audiometer. Test frequencies were 500, 750, 1000, 1500, 2000, 3000 and 4000 Hz. The absolute thresholds and masked thresholds in the presence of TEN were measured using the two-channel OB922 clinical audiometer. The TEN was usually presented at 70 dB/ERB_N. However, a higher level (up to 85 dB/ERB_N) was used for participants having severe of profound hearing loss and a lower level of TEN was used for participants with minimal or mild hearing loss, especially if they complained about the loudness of the TEN at a particular frequency. The level of the signal and the TEN were controlled using the attenuators in the audiometer. The potentiometer controlling the tape inputs was set to give a reading of 0 dB on the VU-meter of the audiometer. The signal level was varied in 2-dB steps to determine the masked thresholds, as recommended by Moore et al. (2004). 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 than the TEN level/ERB_N, and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be present at the signal frequency. If the masked threshold in the TEN was higher than the TEN level/ERB_N by less than 10 dB, and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be absent. If the masked threshold in the TEN was higher than the TEN level/ERB_N by 10 dB or more, but the TEN did not elevate the absolute threshold by 10 dB or more, then the result was considered inconclusive.

Speech identification task

The speech identification abilities were assessed for two different tasks. The speech materials were played through a Philips 729K CD player connected to the audiometer. During the presentation of the stimuli, it was ensured that the VU-meter of the audiometer deflected around 0 dB. The participants were instructed to repeat the speech stimulus heard. The participants were encouraged to respond to as many stimuli as possible and guess the answer if necessary. The responses provided by the subject were recorded using a tape recorder kept in the subject room. These recorded responses were used to establish inter-judge reliability to ensure that there was no tester bias while scoring the responses. Reliability of the responses given by the participants was assessed by using split-half method given by described by Garrett and Woodworth (1966). The reliability co-efficient was 0.8 indicating the responses from the participants were reliable.

Bisyllabic words were presented to obtain speech identification scores under headphones. The presentation level was set at 40 dB SL (ref: pure-tone average) or at most comfortable level. Validity and reliability of this test has been established on native speakers of Kannada (Vandana, 1998). Speech identification scores were assessed for each ear separately. Speech material in the form of consonant-vowel (CV) was used to assess the benefit derived from a hearing aid. Speech material was amplified through a digital hearing aid according to the NAL-NL1 formula (Dillon, 1999). Real ear measurements were done to ensure that the aided responses matched the target gain curve. For the participants without dead regions the digital hearing aid was programmed only for full band amplification. The digital hearing aid was programmed for three different conditions for the participants with dead regions (Figure M.1):

1) fullband amplification
2) amplification up to one octave above the *fe*

3) amplification up to the *fe*

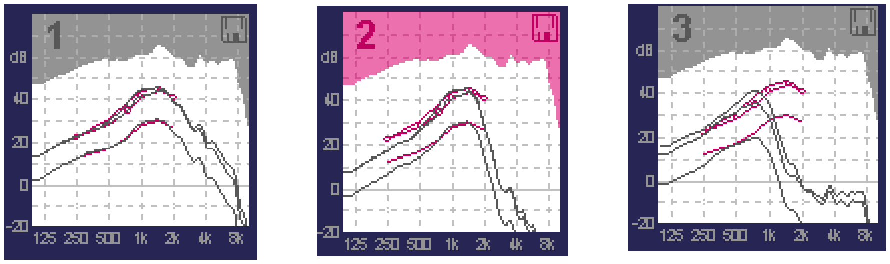

Figure M.1. Graph showing three different amplification conditions for an individual with dead region having *fe* at 1000 Hz.

The same hearing aid was used for all the participants with appropriate sized eartips. Though it is ideal to use custom ear molds while fitting a hearing aid, ear tips were used due to practical constraints of the participants. As the aim of the study was to compare the speech identification scores in different amplification conditions, it was assumed that the effect of eartip would have been similar in all the three amplification conditions. It was ensured that testing in all the three amplification conditions was carried out in one sitting to ensure that insertion depth of the eartips did not vary from one condition to another.

The stimuli were presented at 45 dB HL through the loud speakers of the audiometer placed at a distance of one meter at 45 degree azimuth towards the test ear side. In order to avoid the participation of the non-test ear, it was masked by the presentation of 60 dB SPL broadband noise through an insert receiver. The order of conditions and the list was randomized across participants to control the order effect.

The electroacoustic characteristics of the hearing aid were checked before testing each participant.

Analyses

Statistical Analyses

The data thus obtained were subjected to appropriate statistical analyses, which included t-test for Independent Samples, Paired t-test, nonparametric Chi-square test and Analyses of Variance (ANOVA). All the statistical tests were applied using the Statistical Package for Social Sciences (SPSS) version 14.

Slope estimation

The slope values were estimated in two different methods in ears with dead regions: First by considering the difference in the audiometric thresholds between the *fe* and the previous octave frequency. Second, by considering the difference in the audiometric thresholds between the *fe* and the previous mid-octave frequency. In ears without dead regions, the slope values were estimated by considering the difference between two adjacent corresponding octave/mid-octave frequencies. For convenience sake, the frequency (corresponding to the *fe* in ears with dead regions) in ears without dead regions will be termed as ‘test frequency’. If the audiometric threshold worsened with increasing frequency, then it was denoted as a positive slope, while if the threshold improved with increasing frequency, this was denoted as a negative slope.

Hit rate and Miss rate estimation

To check the efficiency of audiometric data in predicting the presence or absence of a dead region, the hit rate, miss rate, false alarm and correct rejection rates were calculated by comparing the prediction made based on the audiometric criteria with the results of TEN test.

Sequential Information Analyses

The percentage of input information transmitted for a given feature was determined using SINFA Analyses Suite "FIX" software (Mike Johnson, Department of Phonetics & Linguistics, University College London; www.phon.ucl.ac.uk.resource.htm). The consonant features were categorized based upon the classification system given by Ramaswami (1999). However, the consonant /h/ was excluded while carrying out analysis of voicing feature as it is considered as half-vocalic by some of the researchers (Savithri, 1989). The consonants were analyzed to determine the percentage information transmission for the phonetic features of place, manner and voicing (Miller & Nicely, 1955). The first stage was to compile a stimulus-response matrix. In a few instances, the participants failed to respond to the stimuli. These were excluded from the stimulus-response matrix. For each feature, the information transmitted from stimulus to response was computed.

Table M.1.

Place, manner and voicing features for different consonants ('V' indicates voiced and 'UV' indicates unvoiced).

Place/Manner/ Voicing	**Bilabial**		**Labiodental**		**Dental**		**Retroflex**		**Palatal**		**Velar**		**Glottal**	
	UV	**V**	**UV**	**V**	**UV**	**V**	**UV**	**V**	**UV**	**V**	**UV**	**V**	**UV**	**V**
Plosive	p	b			t,	d	ṭ	ḍ			k	g		
Nasal	m				n		ṇ							
Tap								r						
Fricative					s, ʃ								h	
Affricate									tʃ,	dʒ				
Lateral							l, ḷ							
Semivowel				v						y				

CHAPTER IV

RESULTS AND DISCUSSION

Data were collected from 208 individuals (372 ears; 74 females and 134 males) with sensorineural hearing impairment. The data included 195 ears without dead region and 177 ears with dead regions. Individuals with dead regions were further categorized into different groups based on the *fe* of the dead region. Out of 177 ears with dead regions, 43 ears had edge frequency of 1000 Hz, 36 ears had edge frequency of 1500 Hz, 41 ears had edge frequency of 2000 Hz, 24 ears had edge frequency of 3000 Hz and there were 33 ears with edge frequency of 4000 Hz.

The results are discussed under the following sections:

1. Investigation and comparison of slope in ears with and without dead regions
    1.1. Comparison of slope in ears with and without dead regions
    1.2. Efficacy of audiometric data in prediction of the presence or absence of dead regions
2. Investigation and comparison of speech identification abilities in individuals with and without dead regions
    2.1. Speech identification abilities in individuals without dead regions
    2.2. Speech identification abilities in individuals with dead regions
    2.3. Comparison of speech identification abilities in individuals with and without dead regions

3. Investigation of benefit from amplification in individuals with dead regions

3.1. Benefit of amplification

3.2. Effect of amplification conditions in individuals with different *fe*

3.2.1. Consonant identification with fullband amplification

3.2.2. Consonant identification with amplification up to one octave above the *fe* of dead region

3.2.3. Consonant identification with amplification up to *fe* of dead region

3.2.4. Comparison of different amplification conditions

1. Slope of the audiogram

One of the objectives of the present study was to investigate whether audiometric slope can predict the presence or absence of dead regions in ears with sensorineural hearing loss. The slope estimation was carried out as a difference between two adjacent octave and mid octave frequencies. Initial data of 102 ears with dead regions and 165 ears without dead regions were analyzed. The mean, standard deviation and range of slopes in different groups was estimated and analyses were carried out to investigate if there is a significant difference between the slope values in ears with and without dead regions. The slope values in ears without dead regions were compared separately with each subgroup of ears with dead regions. Based on the cut off slope values obtained in the present study and the threshold criteria reported in literature, an attempt was made to predict the presence or absence of dead regions in another sample of 105 ears with sensorineural hearing loss. The predicted results were validated with the results of TEN test. The hit rate, false alarm rate, correct rejection and miss rates in predicting dead regions were calculated for the different criteria developed in the present study.

1.1. Comparison of audiometric slope in ears with and without dead regions

The mean, standard deviation and range of the slope between two octave frequencies in ears with and without dead regions are shown in Tables R.1.1 and R.1.2. It can be observed from Table R.1.1 and R.1.2 that the mean slope (dB/octave) was greater in ears with dead regions when compared to ears without dead regions. The mean slope value was equal to or greater than 20 dB/octave in ears with dead regions having different *fe*. The non-parametric Mann Whitney U test was carried out to compare the slopes in ears without dead region and those with dead region having different *fe*. Results revealed that the difference in mean slope values between the two groups was significant at 0.01 level for all the groups (Z=5.58 for 1000 Hz; Z=4.71 for 1500 Hz; Z=4.23 for 2000 Hz; Z=2.82 for 3000 Hz and Z=3.98 for 4000 Hz).

Table R.1.1

Mean, standard deviation (SD) and range for slope values (dB/octave) in ears with dead regions at different edge frequencies.

Edge Frequency (Hz)	Mean (SD) (dB HL)	Range (dB HL)	
		Minimum	Maximum
1000	31.79 (12.34)	10	50
1500	26.43 (15.62)	5	55
2000	20.71 (11.65)	0	45
3000	20.0 (12.06)	0	40
4000	22.08 (6.2)	15	30

Table R.1.2

Mean, standard deviation (SD) and range for slope values (dB/octave) in ears without dead regions.

Frequency (Hz)	Mean (SD) (dB HL)	Range (dB HL)	
		Minimum	Maximum
1000	4.66 (8.98)	-15	25
1500	7.07 (7.72)	-10	25
2000	8.56 (10.81)	-15	45
3000	10.11 (10.09)	-5	45
4000	10.75 (10.30)	-10	50

Earlier reports on comparison of slope in dB/octave in ears with and without dead regions are inconclusive. Preminger, Carpenter and Ziegler (2005) reported that the slope of the audiogram was significantly higher for ears with high-frequency dead regions (18.9 dB/octave) than for ears without dead regions (11 dB/octave). They further observed that 87% of participants having a slope value greater than 20 dB/octave met the criteria for the presence of a dead region on TEN test. Vinay and Moore (2007a) also reported a significant difference between the slope values in ears with and without dead regions. In both the studies, the slope values were calculated *inside* the area of the dead regions. However, contrasting results were obtained by Aazh and Moore (2007) who reported no significant difference in the slope values (dB/octave) in ears with and without dead regions at 4000 Hz. They considered the difference between audiometric thresholds at 4000 and 8000 Hz as the slope value *inside* the area of the dead regions and the difference in the audiometric thresholds at 2000 and 4000 Hz as the slope value *outside* the area of the dead region. The results of the present study contradict the results obtained by Aazh and Moore (2007) but are in agreement with the earlier studies (Preminger et al., 2005; Vinay & Moore, 2007a). The results of the present study indicate that the slope outside the dead region is also steeper in ears with dead region. It may be noted that Aazh and Moore (2007) considered only ears with edge frequency of 4000 Hz and the individuals had audiometric thresholds between 60 and 85 dB HL at 4000 Hz. The present study included participants having *fe* at 1000, 1500, 2000, 3000 and 4000 Hz and the audiometric threshold in individuals with sensorineural hearing loss ranged from minimal to profound degree of hearing loss. However, individuals were not categorized based on the degree of hearing loss. However, a preliminary glance at the individual data revealed that lesser the degree of hearing loss, greater the slope values. However, it can be observed from Table 1 and 2 that both the groups had a large standard deviation indicating individual variability in the slope values and there was an overlap in the range values. Earlier studies on slope inside the dead regions (Preminger et al., 2005;

Vinay & Moore, 2007a) also indicate an overlap in the range of the slope values in ears with and without dead regions.

Table R.1.3

Mean, standard deviation (SD) and range for slope values (dB) between two adjacent mid-octave frequencies in ears with dead regions at different edge frequencies.

Edge Frequency (Hz)	**Mean (SD)**	**Range (dB)**	
		Minimum	**Maximum**
1000	20.71 (10.16)	10	35
1500	20.71 (12.22)	5	40
2000	9.29 (5.98)	0	30
3000	13.33 (10.08)	5	40
4000	16.25 (8.01)	5	30

Table R.1.4

Mean, standard deviation (SD) and range for slope values (dB) between two adjacent mid-octave frequencies in ears without dead regions.

Frequency (Hz)	**Mean (SD)**	**Range (dB)**	
		Minimum	**Maximum**
1000	2.47 (5.7)	-10	20
1500	4.6 (5.97)	-5	25
2000	4.08 (6.13)	-10	20
3000	6.21 (8.0)	-5	40
4000	4.66 (4.75)	-5	20

The mean, standard deviation and range of the slope between two mid-octave frequencies in ears with and without dead regions are shown in Tables R.1.3 and R.1.4. In ears with dead region, the slope was calculated as the difference between the threshold at the *fe* and the mid-octave lower than the *fe*. In ears without dead region, the slope was calculated as the difference between the threshold at the test frequency and the mid-octave lower to the test frequency. The mean slope per mid-octave values, for ears with dead regions was higher than those obtained for ears without dead regions. The non-parametric Mann Whitney U test revealed that the differences in slope values were statistically significant at 0.01 level for all the groups ($Z=5.74$ for 1000 Hz; $Z=5.08$ for 1500 Hz; $Z=3.53$ for 2000 Hz; $Z=3.08$ for 3000 Hz and $Z=4.57$ for 4000 Hz). The mean slope value for mid-octave was lesser than slope per octave frequencies in both the groups of ears with and without dead regions at all frequencies. However, the difference in the slope value was more for ears with dead regions. There is a dearth for studies comparing the slope per mid-octaves in ears with and without dead regions.

It has been reported that steeper slope in ears with dead regions may be due to the need for downward spread of the vibration pattern to a lower characteristic frequency in ears with dead regions (Moore, 2001). Because of the phenomenon of off-frequency listening, the neurones that have characteristic frequency adjacent to the signal respond when a tone is presented in the area of a dead region (Patterson & Moore, 1986). Thus it is expected that ears with high-frequency dead region are associated with a steep slope of the audiogram in the frequency range adjacent to the *fe* of the dead region. However, it has also been reported that dead regions do sometimes occur when the audiometric slope is not steeply sloping (Moore, 2001) and the results of the present study reinforce this consensus especially when the *fe* is 2000 Hz or greater.

1.2. Efficacy of audiometric data in prediction of the presence or absence of dead regions

The present study analyzed whether the presence or absence of a dead region can be predicted from the audiogram. Based on the results of the present study and earlier investigations reported in literature, the following criteria were considered as the indicators for presence or absence of dead regions at a particular frequency:

- Criteria I: Mean – 1 SD of slope per octave frequencies obtained in the present study, for ears with dead region
- Criteria II: Mean – 1 SD of slope per mid octave frequencies obtained in the present study for ears with dead region
- Criteria III: Audiometric threshold equal to or greater than 75 dB HL (Vinay & Moore, 2007a)
- Criteria IV: Combination of audiometric threshold equal to greater than 75 dB HL and Mean – 1 SD of slope per octave frequencies obtained in the present study, for ears with dead region.
- Criteria V: Combination of audiometric threshold equal to or greater than 75 dB HL and Mean – 1 SD of slope per mid octave frequencies obtained in the present study for ears with dead region

These criteria were used on another sample of 105 ears with sensorineural hearing loss to check for the presence or absence of dead region. TEN test was also administered on all these ears to confirm the presence or absence of dead regions. The measures of hit rate, miss rate, correct rejection and false alarm rates obtained when the presence or absence of dead region was predicted based on these criteria are given in Table R.1.5.

Table R.1.5

Hit rate, miss rate, correct rejection and false alarms for the different criteria. Numbers in brackets indicate percentage values.

Frequency (Hz)	Criteria	Hit Rate	Miss Rate	Correct Rejection	False Alarm
	Criteria I	11 (73)	4 (27)	29 (97)	1 (3)
	Criteria II	10 (67)	5 (33)	28 (93)	2 (7)
1000	Criteria III	14 (93)	1 (7)	29 (97)	1 (3)
	Criteria IV	10 (67)	5 (33)	28 (93)	2 (7)
	Criteria V	9 (60)	6 (40)	27 (90)	3 (10)
	Criteria I	10 (71)	4 (29)	28 (93)	2 (7)
	Criteria II	9 (64)	5 (36)	28 (93)	2 (7)
1500	Criteria III	13 (93)	1 (7)	28 (93)	2 (7)
	Criteria IV	9 (64)	5 (36)	26 (87)	4 (13)
	Criteria V	8 (57)	6 (43)	27 (90)	3 (10)
	Criteria I	12 (67)	6 (33)	27 (90)	3 (10)
	Criteria II	13 (72)	5 (28)	27 (90)	3 (10)
2000	Criteria III	18 (100)	0 (0)	26 (87)	4 (13)
	Criteria IV	11 (61)	7 (39)	25 (83)	5 (17)
	Criteria V	12 (67)	6 (33)	24 (80)	6 (20)
	Criteria I	8 (67)	4 (33)	24 (80)	6 (20)
	Criteria II	8 (67)	4 (33)	21 (70)	9 (30)
3000	Criteria III	12 (100)	0 (0)	25 (83)	5 (17)
	Criteria IV	8 (67)	4 (33)	23 (77)	7 (23)
	Criteria V	7 (58)	5 (42)	20 (67)	10 (33)
	Criteria I	11 (61)	5 (39)	22 (73)	8 (27)
	Criteria II	9 (56)	7 (44)	21 (70)	9 (30)
4000	Criteria III	16 (100)	0 (0)	20 (67)	10 (33)
	Criteria IV	11 (61)	5 (39)	21 (70)	9 (30)
	Criteria V	8 (50)	8 (50)	18 (60)	12 (40)

It can be observed from Table R.1.5 that, the hit rate for criteria I was around 70% for f_e of 1000 and 1500 Hz and the hit rate decreased for higher f_e. For criteria II, the hit rate values were comparatively lesser than those obtained for criteria I in a majority of the groups. The correct rejection rate was around 90 % for *fe* of 2000 Hz or lesser but decreased to around 70 % for *fe* of 4000 Hz for all the criteria. Studies have concluded that the phenomenon of off frequency listening may be responsible for the subject to respond for the tone at a particular frequency despite having 'infinite' hearing loss at that frequency (Patterson & Nimmo-smith, 1980). Thresholds obtained due to the detection of a tone by off-frequency leads to a lower threshold and hence may fail to indicate the presence of a dead region. If there is on-frequency hearing at a particular frequency and off-frequency hearing in the neighboring frequency, it leads to a steeply sloping pattern of hearing loss. However, the results of the presents study indicate that slope may not be a reliable indicator for the presence of a dead region especially for identifying ears with *fe* at higher frequencies.

As it has been reported that ears with dead region have very high audiometric threshold (Moore, 2001), it was thought that the possibility of predicting the presence or absence of a dead region might be enhanced by supplementing the information about audiometric threshold criterion established at a particular frequency. Therefore, calculations were obtained in terms of the audiometric thresholds (criteria III). An audiometric threshold criterion of 75 dB HL was considered based on the results of the present study and the study by Vinay and Moore, (2007a) which reported that a threshold criterion of 75 dB HL had a reasonably good hit rate and correct rejection value for most of the frequencies in predicting the presence or absence of a dead region. The results of the present study indicate that for criteria III, both the hit rate and correct rejection were reasonably high for frequencies at 1000, 1500, 2000 and 3000 Hz. This shows that audiometric threshold criterion may reliably predict the presence or absence of a dead region for the audiometric frequencies lesser than 4000 Hz. The hit rate for criteria III was considerably higher when compared to criteria II and I at all frequencies. However, when the test frequency was 4000 Hz, though the hit rate was high, the correct rejection was low. The hit rate and correction rejection rate for criteria III indicated higher sensitivity and lower specificity values than those reported by earlier studies (Aazh & Moore, 2007; Vinay & Moore, 2007a). In the present study, the hit rate was above 90% for all frequencies and reached 100% for frequencies above 1500 Hz but the correct rejection rate reduced from around 100% at 1000 Hz to around 70% at 4000 Hz. In the present study, the hit rate calculation for slope and/or threshold criteria was done considering the number of ears diagnosed as having no dead region or a dead region at a particular *fe* based on the results of the TEN (HL) test. This may have resulted in a higher hit rate for predicting the presence or absence of a dead region using any of the mentioned criteria. Also, it has been shown that, there is a very good correspondence between the results of the TEN test and PTCs (Kluk & Moore, 2005). Other possible reason may be due to the differences in the slope estimation method used.

Previous studies carried out have considered the criteria of either audiometric slope or threshold separately (Aazh & Moore, 2007; Preminger et al., 2005; Vinay & Moore, 2007a). However, the present study included additional criteria of a combination of audiometric threshold and slope to predict the presence or absence of dead regions. Strict criteria including a combination of audiometric slope and threshold to predict the presence or absence of a dead region also resulted in a hit rate of around 60% for most frequencies when slope values were considered either between two octaves or two adjacent mid-octave frequencies. Thus there was a reduction in the hit rate values when audiometric slope combined with the threshold was considered as criteria rather than audiometric slope alone to predict the presence of dead regions in individuals with sensorineural hearing loss. Also, hit rate of ears at all frequencies was less for criteria IV and criteria V when compared to that of criteria III. However, the correct rejection rate increased slightly for test frequencies above 1500 Hz when criteria IV were used when compared to criteria III.

To summarize, the results of the present study indicated that the slope values for ears with dead regions were significantly higher when compared to ears without dead regions but there was an overlap in the range of slope values between the two groups. Audiometric threshold criteria is better than the slope criteria in predicting dead regions and may be taken as a preliminary indicator for the presence or absence of a dead region at frequencies of 3000 Hz and below since it leads to both high hit rate and correct rejection rate.

2. Investigation and comparison of speech identification scores for words in individuals with and without dead regions

The present study compared speech identification abilities for words on 63 participants (102 ears) with dead regions and 44 individuals (87 ears) without dead regions (Table R.2.1). Previous research suggests that the presence of sensorineural hearing impairment may reduce the contribution of speech information in a given frequency region to speech understanding (Pavlovic, Studebaker & Sherbecoe, 1986; Studebaker, Sherbecoe, McDaniel & Gray, 1997). However, there is dearth of studies comparing the speech identification abilities in individuals with sensorineural hearing loss having dead regions and no dead regions.

2.1 Speech identification abilities in individuals without dead regions

The data were categorized based on the ear, gender, age, degree and configuration of hearing loss. The individuals were divided into two groups based on the age, Group I with the age ranging from 30 to 59 yr and Group II with the age ranging from 60 to 79 yr. The individuals were grouped under minimal, mild, moderate and moderately severe degree based upon the classification given by Clark (1981). The individuals were also grouped according to the configuration of hearing loss as flat and sloping hearing loss. Table R.2.1 shows the mean and standard deviation of speech identification scores for different groups. The overall mean speech identification score was 17.95 with a standard deviation of 5.05. The mean speech identification score for the right ear was slightly higher than for the left ear. However Independent Sample t-test revealed that the difference in scores between the two ears was not statistically significant (t = 0.08; p>0.05). Also, the results of Independent Sample t-test revealed no significant effect of gender on the speech identification scores (t=1.7; p>0.05). Hence the data were merged in terms of ears and gender for further analyses.

Table R.2.1

Mean and standard deviation values for speech identification scores for words in individuals without dead regions

	Group I		**Group II**	
	Males	**Females**	**Males**	*Females*
Right ear	17.31(4.87)	20.18(3.87)	17.11(5.78)	18.5(2.12)
Left ear	18.21(3.68)	19.4(4.74)	17.0(6.38)	15.0(0)
Right + left ear	17.78(4.24)	19.81(4.21)	17.06(6.0)	17.33(2.52)
Total	18.67(4.3)		17.08(5.79)	

A 3-way ANOVA was carried out to find out if there was a main effect of age, degree and configuration of hearing loss on the speech identification scores. As shown in Table R.2.2 there was a main effect of age and degree of hearing loss on speech identification scores but the configuration of hearing loss did not have a significant on the speech identification scores. There was no significant two way or three way interactions among the variables.

Table R.2.2

Results of ANOVA indicating 'F' values for different variables in individuals without dead regions

Variables	F (df)	p
Age	F(1,74) = 20.3	<0.001
Degree of HL	F(3,74) = 8.76	<0.001
Configuration of HL	F(1,74) = 0.00	>0.05
Age*Degree of HL	F(3,74) = 2.22	>0.05
Age*Configuration of HL	F(1,74) = 0.83	>0.05
Degree of HL*Configuration of HL	F(2,74) = 1.61	>0.05
Age*Degree*Configuration of HL	F(1,74) = 0.02	>0.05

Effect of age: The results of the present study are in consensus with the results of earlier studies reporting the independent effects of age related changes to the reduced speech identification abilities in individuals with sensorineural hearing loss without dead regions. Studying the effect of age on speech identification scores has been a challenging task as a majority of the older individuals also have cochlear hearing loss. Many reports have suggested that there is a significant effect of age on auditory thresholds, with reduced auditory sensitivity and increased thresholds at all frequencies in the older groups (Dubno, Horwitz & Ahlstrom, 2003; Silva & Fietosa, 2006; Stelmachowicz, Beauchaine, Kalberer, & Jesteadt, 1989) though age associated hearing loss initially affects higher frequencies (Quaranta, Sallustio, & Quaranta, 2001; Stelmachowicz et al., 1989). A few investigators (ANSI, 1969; ANSI, 1997; Fletcher, 1953; Pavlovic, 1987) have reported that most of the speech information will be present in the higher frequencies and hence poor speech identification abilities in the elderly could be due to high frequency hearing loss. Dubno, Dirks and Morgan, (1984) found that the younger and older adults with similar hearing thresholds also exhibited comparable speech identification scores. Contrary to these results other studies have shown that the mean data for young and elderly listeners usually show small but consistent differences even when the groups were equated for peripheral hearing sensitivity (CHABA, 1988; Dubno, Dirks, & Morgan, 1982; Findlay & Denenberg, 1977; Townsend & Bess, 1980). These differences might be attributable to peripheral or cognitive factors (CHABA, 1988).

In an attempt to investigate the factors other than hearing loss that can affect speech identification scores in elderly individuals, the correlations among specific psychophysical variables and speech identification scores as a function of age have been investigated (Dreschler, 1980; Dreschler & Plomp, 1980; Festen & Plomp, 1983; Stelmachowicz, Jesteadt, Gorga & Mott, 1985; Tyler & Summerfield, 1980). It has been reported that the suprathreshold functions such as frequency, intensity and temporal discrimination may be impaired in older individuals in addition to an increase in the absolute thresholds and that these impairments may adversely affect the speech identification abilities in individuals with sensorineural hearing loss (Cheesman, Hepburn, Armitage & Marshall, 1995; Fitzgibbons & Gordon-Salant, 1994; Patterson, Nimmo-Smith, Weber & Milroy, 1982; Schneider, 1997). Other factors that can have an effect on the speech identification scores of the elderly individuals include neural degenerations (Dubno et al., 1984; Humes & Christopherson, 1991), cognitive decline (Corso, 1971; Plomp & Mimpen, 1979; Townsend & Bess, 1980; Salthouse, 1996).

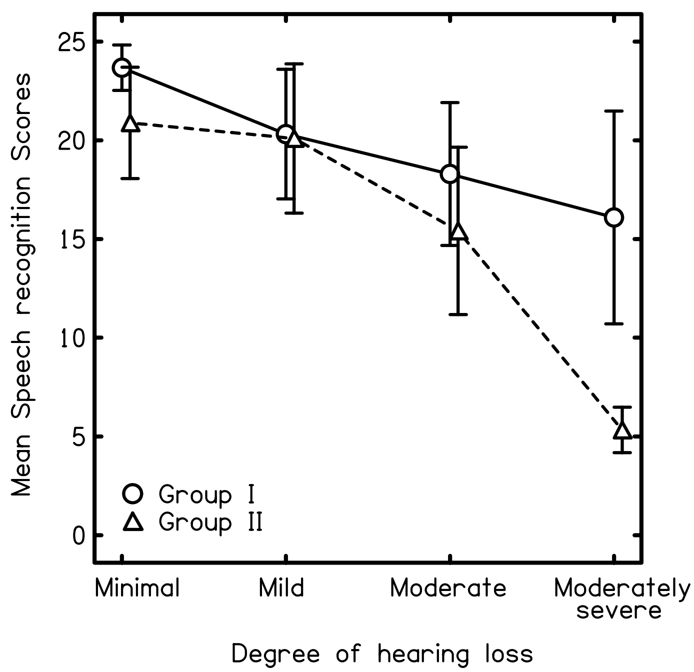

Figure R.2.1. Speech identification scores for Group I and Group II individuals across different degrees of hearing loss

Figure R 2.1, shows the speech identification scores for Group I and Group II matched for degree of hearing loss. It can be observed that the speech identification scores of Group II are poorer than those of Group I for all the groups except those with mild hearing loss. The results of ANOVA revealed no significant interaction between degree of hearing loss and age of the individuals. These results suggest that factors other than hearing loss were responsible for the poorer performance in geriatric individuals. Factors related to cognitive decline have not been assessed in the present study but effect of such factors would be minimal as words were used to assess speech identification abilities. The difference in speech identification abilities between the two groups may be due to reduced frequency selectivity, temporal resolution and/or neural degeneration in the geriatric population.

Effect of degree and configuration of hearing loss: Table R.2.3 shows the speech identification abilities of individuals with different degrees of hearing loss. Results of the Bonferroni posthoc test revealed that the speech identification scores for individuals having minimal degree sensorineural hearing loss were significantly ($p<0.01$) higher from those having moderate and moderately severe degree of hearing loss. Speech identification scores of individuals having mild degree sensorineural hearing loss was significantly higher from those having moderately severe degree of hearing loss ($p<0.01$) and there was a significant difference ($p<0.05$) between moderate and moderately severe degree of hearing loss. However, there was no significant difference in the speech identification scores ($p>0.05$) for the other groups.

Table R.2.3

Mean and standard deviation for speech identification scores in different degrees of hearing loss

Severity of hearing loss	**Speech Identification Scores for words**	
	Mean	*Standard deviation*
Minimal	21.64	4.27
Mild	20.21	3.44
Moderate	17.0	4.12
Moderately severe	13.79	6.60

The results of the present study are in consensus with the earlier reports regarding effect of degree of hearing loss on the speech identification abilities in individuals with sensorineural hearing loss. Crandell (1993) concluded that speech identification abilities were affected in individuals with mild sensorineural hearing loss. Previous studies have shown that hearing sensitivity is one of the main factors affecting speech identification abilities in individuals with hearing impairment (Plomp, 1978). According to the articulation index (French & Steinberg, 1947), the predicted speech identification performance is inversely proportional to the degree of hearing loss, for individuals with hearing loss of cochlear origin.

Studies have concluded that individuals with mild to moderate sensorineural hearing loss have reduced speech identification abilities (Davis, Elfenbein, Schum & Bentler, 1986; Elfenbein, Hardin-Jones & Davis, 1994; Norbury, Bishop & Briscoe, 2001). Hicks and Tharpe (2002) concluded that individuals with mild to moderate degree of sensorineural hearing loss showed reduced speech identification abilities. Also, it is well established that individuals with mild or moderate hearing losses can usually understand speech better than individuals having severe to profound hearing loss (Carney & Moeller, 1998; Moore, 1995). These studies have not differentiated between individuals with and without dead regions. In the present study, individuals were classified based on the presence or absence of dead regions and there were no individuals with severe or profound degree of hearing loss without dead regions. However, the mean speech identification scores decreased with increase in degree of hearing loss and the statistical analysis showed a significant main effect of degree of hearing loss on speech identification scores.

The mean speech identification scores for the two configurations of hearing loss, flat and sloping hearing loss are depicted in Table R.2.4. The mean score for individuals with flat hearing loss was poorer than those with sloping hearing loss but the difference was not statistically significant ($t = 1.53$; $p>0.05$). Figure R.2.2 shows the speech identification scores for ears with different configuration of hearing loss matched for degree of hearing loss. ANOVA revealed that there was no significant interaction effect between degree and configuration of hearing loss ($p>0.05$).

Table R.2.4

Mean and standard deviation for speech identification scores for words in individuals without dead regions for different configuration of hearing loss

Audiometric Configuration	**Speech Identification Scores for words**	
	Mean	**Standard deviation**
Flat	16.07	5.51
Sloping	18.32	4.92

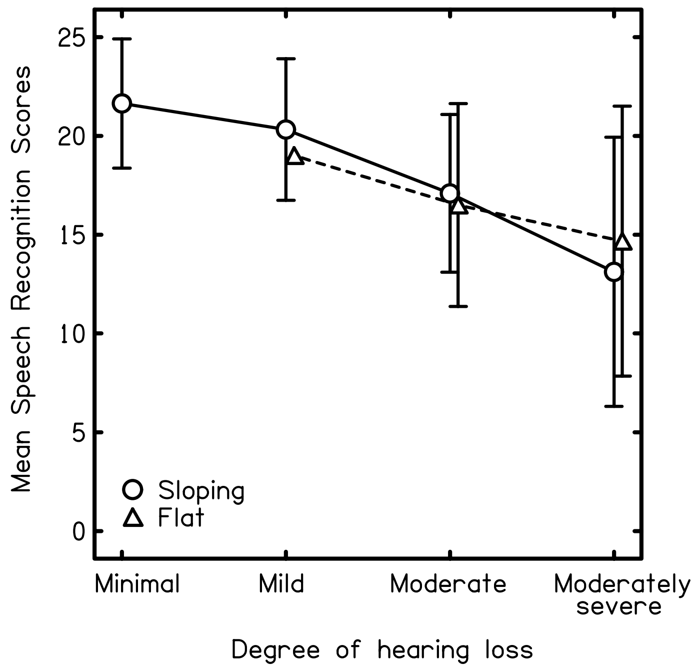

Figure R.2.2. Speech identification scores for individuals with flat and sloping configuration across different degrees of hearing loss

These results are in consensus with the reports of Turner, Souza and Forget (1995) who reported that there was no significant difference in the speech identification scores for individuals with flat and sloping configuration. Turek, Dorman, Franks and Summerfield, (1980) studied individuals with sensorineural hearing losses of both flat and sloping configuration in identifying stop consonant place of articulation and reported that there was no significant effect of audiometric configuration on speech identification abilities in these individuals. Beattie and Zipp (1990) reported similar results. Beattie and Warren (1983) tested individuals with mild-to-moderate sensorineural hearing loss and found that individuals with steeply sloping audiograms exhibited more gradual word identification slopes (1.6%/dB) than individuals with flat or moderately falling audiometric configurations (2.5%/dB). They also concluded that the magnitude of hearing loss and audiometric configuration did not significantly affect the slope of word identification.

Contrary to these findings, some of the studies have shown that the identification of consonants is dependent upon the audiometric configuration (Dubno, Dirks & Schaefer, 1987). Probably, a difference in the speech identification scores would have been observed in the present study if testing were carried out in the presence of noise. Other possible reason for not observing an effect of configuration on speech identification scores could be related to the speech material used in the study. Geetha, Ashly and Yathiraj (2005) observed that slope of the simulated hearing loss affected the identification of high frequency words in individuals with normal hearing. Similar results were obtained in previous studies (Horwitz, Dubno & Ahlstrom, 2002; Silman & Silverman, 1991; Strickland, Viemeister, Van Tasell, & Preminger, 1994). The word list used to assess speech identification scores in the present study was phonetically balanced. Probably the scores for individuals with sloping hearing loss would have been lesser than that of those with flat configuration of hearing loss if a high frequency word list were used for testing.

Thus, from the results of the present study, it may be concluded that the age and severity of hearing loss affect the speech identification performance in individuals with sensorineural hearing loss. However, the configuration of hearing loss does not have a significant effect on the speech identification abilities in these individuals and there is no interaction between degree and configuration of hearing loss.

2.2 Speech identification abilities in individuals with dead regions

This group consisted of 102 ears (63 individuals), which were categorized based on the ear, gender, age, degree of hearing loss and *fe* of the dead regions. All individuals had sloping hearing loss with a difference of more than 25 dB between the lowest and the highest audiometric frequency tested. Based on the *fe* determined by the results of TEN (HL) test, individuals were grouped as those having *fe* at 1000, 1500, 2000, 3000 and 4000 Hz. The criteria used for classification into other groups were same as those used for classifying individuals without dead regions.

Table R.2.5 shows the mean and standard deviation of speech identification scores for Group I and Group II with dead regions. The overall mean speech identification scores of individuals with dead regions were 14.12 with a standard deviation of 3.74. The mean speech identification scores for the right ear were slightly higher than that for the left ear. However, the results of the Independent Sample t-test revealed that the difference in scores was not statistically significant ($t = 0.26$; $p>0.05$). Hence, the data of the two ears were merged for further analysis. The data from males and females were also merged as the Independent Sample t-test revealed that there was no significant difference in scores for males and females ($t = 0.37$; $p>0.05$).

Table R.2.5

Mean and standard deviation values (in brackets) for speech identification scores for individuals with dead regions

	Adults		**Geriatrics**	
	Males	**Females**	**Males**	**Females**
Right ear	15.25(3.21)	13.82(4.35)	13.95(3.48)	12.8(3.7)
Left ear	14.35(3.48)	15.38(5.39)	13.52(3.77)	12.8(3.56)
Right + left ear	14.79(3.33)	14.47(4.74)	13.73(3.6)	12.8(3.42)
Total	14.67(3.86)		13.54(3.55)	

A 3-way ANOVA was carried out with age, degree of hearing loss and *fe* as independent factors and speech identification scores as dependent variable. It can be observed from Table R.2.6 that there was a main effect of age, degree of hearing loss and *fe* of the dead region on speech identification scores. There was no three way interaction among age, *fe* and degree of hearing loss on the speech identification scores There was no significant interaction effect between age and *fe* but a significant interaction effect was seen between age and degree of hearing loss {$F (3, 71) = 3.04$; $p<0.05$}. This interaction effect was seen probably because Group I individuals with moderate hearing loss had better speech identification scores than those with mild hearing loss as shown in Figure R.2.3.

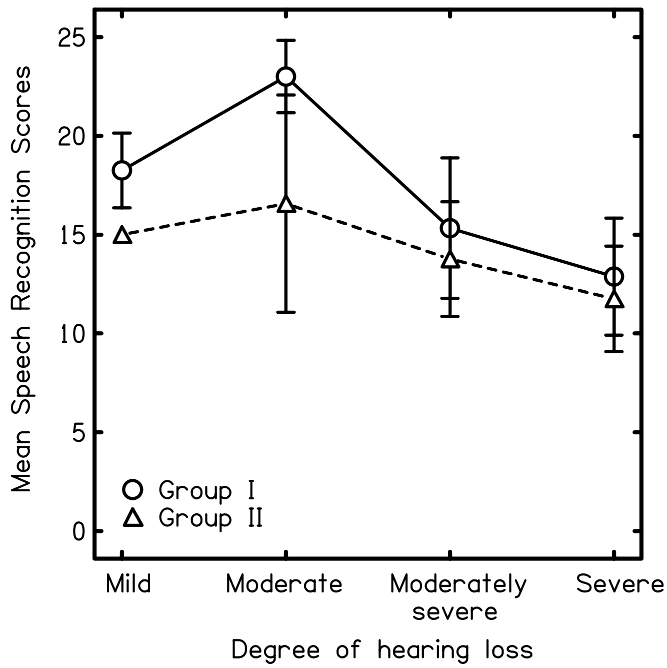

Figure R.2.3. Speech identification scores for words in Group I and Group II for different degrees of hearing loss in individuals with dead regions

Table R.2.6

Results of ANOVA indicating 'F' values, degrees of freedom (df) & significance value(p) for variables affecting speech identification scores in individuals with dead regions

Variables	**F (df)**	**p**
Age	F (1, 71)=7.43	<0.01
Degree of HL	F (3,71)=8.08	<0.001
Edge frequency	F (4,71)=4.2	<0.01
Age*Degree of HL	F (3,71)=3.08	<0.05
Degree of HL*Edge frequency	F (9,71)=2.99	<0.01
Age*Edge frequency	F (4,71)=2.3	>0.05
Age*Degree of HL*Edge frequency	F (4,71)=1.11	>0.05

Effect of *fe* of dead region:

The mean speech identification scores for ears with dead regions having different *fe* are depicted in Table R.2.7. It can be observed from the table that the mean speech identification scores increased with increase in the *fe* in individuals with dead regions. Bonferroni posthoc test revealed that the speech identification scores of ears having *fe* at 1000 Hz was significantly different from those having *fe* at 2000 Hz ($p<0.01$); 3000 Hz ($p<0.001$) and 4000 Hz ($p<0.001$). The speech identification scores of ears having *fe* at 1500 Hz differed significantly from those having *fe* at 4000 Hz ($p<0.05$). However, there was no significant difference among ears with other *fe* in terms of the speech identification scores ($p>0.05$).

Table R.2.7

Mean and SD for speech identification scores (SIS) and mean PTA1 and PTA2 for ears with dead regions having different fe

Edge frequency (Hz)	**Mean SRS for words (SD)**	**Mean PTA1 (SD) in dB HL**	**Mean PTA2 (SD) in dB HL**
1000	12.29(2.53)	75.59 (7.63)	94.1(9.87)
1500	12.82(2.34)	71.28(6.25)	88.18(9.85)
2000	14.74(3.8)	67.02(7.57)	82.46(6.73)
3000	16.75(3.81)	54.16(15.56)	72.36(11.31)
4000	16.59(4.12)	55.58(12.94)	70.58(10.37)

Note. SD indicates 'Standard Deviation'; PTA indicates 'Pure Tone Average'

The results of the present study are in agreement with that reported by Vickers, Moore and Baer, (2001). Though Vickers et al. (2001) did not categorize the individuals based on the *fe* and analyzed the results, inspection of their data reveals that the speech identification scores deteriorated as the *fe* lowered in individuals with high frequency dead regions. This may be due to the fact that individuals with lower *fe* get limited information due to the presence of extensive dead regions. Turner and Brus (2001) reported that speech identification abilities of individuals with hearing impairment improved as the low pass cut-off frequency increased from 560 Hz to 2800 Hz. The low pass cut-off frequency may be compared to the *fe* of the dead region. Earlier Wang, Reed and Bilger, (1978) had observed similar results for normal hearing listeners.

Comparison of pure tone averages of individuals having different *fe* in the present study shows that there were not much difference in the PTA1 (averages of thresholds at 500, 1000 & 2000 Hz), but PTA2 (averages of thresholds at 1000, 2000 and 4000 Hz) increased with decrease in the *fe* (Table R.2.7). As most of the speech information is present in the higher frequencies (Fletcher, 1953; Pavlovic, 1987; ANSI, 1997), speech identification scores reduced with increase in high frequency hearing loss. Several studies have shown that only limited information can be extracted from frequency components of speech falling in a dead region (Vickers et al., 2001; Vinay & Moore, 2007b). It has been shown that speech intelligibility will be relatively poor when extensive dead regions are present within the frequency range that is most important for speech intelligibility (Moore, 2001). However, there is a dearth in literature regarding speech identification abilities in individuals with dead regions having different *fe*.

<u>Effect of age</u>: There is a lack of studies investigating the effect of age on speech identification scores in individuals with sensorineural hearing loss having dead regions. However, as discussed in the previous section, results of a majority of the studies on

individuals with sensorineural hearing loss have revealed a significant reduction in speech identification scores with increase in age (Plomp & Mimpen, 1979; Sommers & Danielson, 1999). Studies have also shown that factors other than cochlear hearing loss contribute to the age related deficits in spoken word identification tasks (Townsend & Bess, 1980; Wingfield, Poon, Lombardi & Lowe, 1985). The reduced speech identification scores in older individuals have been attributed to a number of factors including neural degeneration (Dubno et al., 1984; Humes & Christopherson, 1991) and cognitive decline (Wingfield, Aberdeen & Stine, 1991; Wingfield, Lindfiled & Goodglass, 2000). Probably the factors that affect the speech identification scores for Group II individuals without dead regions also have an effect on the speech identification scores for Group II individuals with dead regions.

<u>Effect of degree of hearing loss</u>: Table R.2.8 shows the speech identification abilities of individuals with dead regions having different degrees of hearing loss. The results of the present study indicated that degree of hearing loss had a main effect on the speech identification scores. Results of the Bonferroni posthoc test revealed that there was a highly significant difference ($p<0.01$) in the speech identification scores of individuals having mild degree and those individuals having severe degree of hearing loss as well as between individuals having moderate degree hearing loss and those individuals having moderately severe or severe degree of hearing loss. There was a significant difference ($p<0.05$) in the speech identification scores for individuals having mild degree and those having moderately severe degree of hearing loss. However, there was no significant difference in the speech identification scores ($p>0.05$) between other groups.

Table R.2.8

Mean and standard deviation for speech identification scores in different degrees of hearing loss

Degrees of Hearing loss	Speech Identification Scores for words	
	Mean	**Standard deviation**
Mild	17.6	2.19
Moderate	18.28	5.9
Moderately severe	15.11	3.2
Severe	12.52	3.04

The results of the present study are in consensus with the earlier reports on the speech identification difficulties in individuals with sensorineural hearing loss with dead regions (Preminger et al. 2005). A higher degree of hearing loss is associated with poor speech identification abilities due to the severity of hearing loss and the limited audibility of the speech signal regardless of whether the subject has dead regions. Thus, the results of the present study highlight the effect of age, degree of hearing loss and *fe* of the dead region on speech identification abilities in individuals with dead regions.

2.3 Comparison of speech identification abilities in individuals with and without dead regions

An attempt was made to investigate the effect of dead region / *fe* of dead region on speech identification scores when the degree of hearing loss was matched in the two groups. For this comparison, only individuals having moderately severe degree of hearing loss and sloping configuration were considered since this category had more number of individuals in both the groups (47 ears with dead regions and 14 ears without dead region) for comparison. The mean and standard deviation for speech identification scores in different groups are depicted in Figure R.2.4.

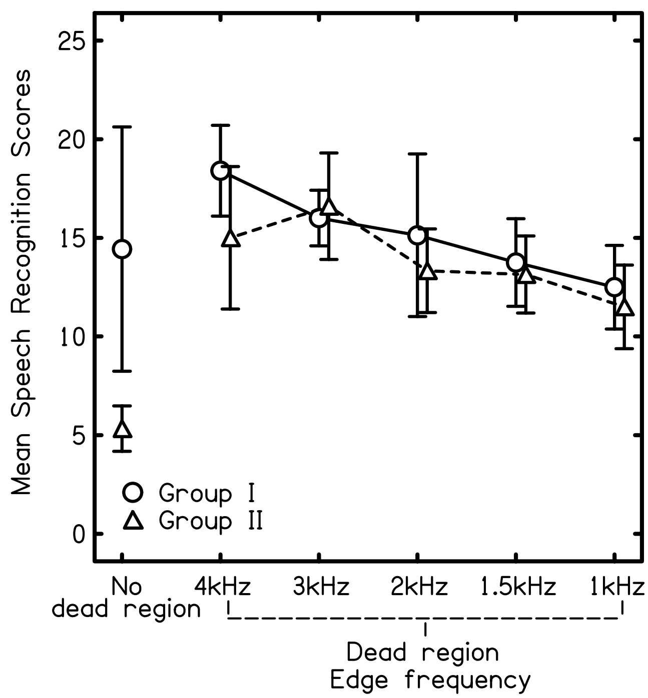

Figure R.2.4. Mean speech identification scores for group I and group II individuals with and without dead regions

A non-parametric Kruskal-Wallis Chi square test was carried out to investigate the effect of presence of dead regions or *fe* of the dead regions on the speech identification scores for Group I and Group II population. The results of the analyses indicated no significant effect of *fe* or dead region on the speech identification abilities in Group I {$\chi(5) = 5.58$, $p > 0.05$) and group II {($\chi(5) = 10.17$, $p > 0.05$). This shows that when the degree of hearing loss is matched, presence of dead region does not have a significant effect on the speech identification abilities in Group I or Group II. However, it can be observed from Figure 2.4 that the mean speech identification scores consistently decreased as the *fe* of the dead region decreased. This may be due to the fact that individuals with lower *fe* get limited information due to the presence of extensive dead region. This is an expected result since the extent of dead region is reduced as the *fe* is increased resulting in increased speech identification abilities in these individuals. It may also be observed that the difference in the speech identification scores between Group I and Group II was more in individuals without dead regions when compared to individuals with dead regions. In fact, Group II individuals without dead regions had poorer scores than individuals with dead regions in that group. As mentioned in the previous sections, a number of factors other than those related to hearing loss also have an effect on speech identification scores in Group II individuals (Dubno et al., 1984; Humes & Christopherson, 1991; Wingfield, Aberdeen & Stine, 1991; Wingfield, Lindfiled & Goodglass, 2000) and Group II individuals with and without dead regions were not matched in terms of these factors. So it is possible that factors other than hearing loss have affected speech identification scores more in Group II individuals without dead regions.

Previous studies have indicated that higher thresholds in individuals with hearing impairment are responsible for poor speech identification performance (Ching, Dillon & Byrne, 1998; Dubno, Dirks & Ellison, 1989; Hogan & Turner, 1998; Kamm, Dirks &

Bell, 1985; Turner & Robb, 1987). Thus the audibility of the signals is one of the major factors affecting speech identification scores in individuals with or without dead regions. Some of the studies have reported that the reduction in the speech identification scores seen in individuals with sensorineural hearing impairment depends on the presence or absence of dead regions (Vickers et al., 2001). It may be observed that Vickers et al. (2001) did not compare speech identification abilities in threshold-matched individuals with and without dead regions. They also reported that individuals with dead regions have abnormally high audiometric thresholds leading to poor audibility and Moore (2001) attributed the reduction in the speech identification scores to poor audibility. In the present study, when the degree of hearing loss was matched across both the groups, results indicated that individuals with and without dead regions perform similarly on the speech identification task. The results of the present study reinforce the concept that audibility is a major factor for reduced speech identification abilities in individuals with and without dead regions. However, though not significant, the results showed a trend of decreased speech identification scores with a decrease in the *fe* of the dead regions suggesting that *fe* also has an effect on the speech identification scores.

2.3.1 Identification of consonants by individuals with and without dead regions

Studies have been carried out comparing the consonant feature identification in individuals with and without dead regions (Baer, Moore & Kluk, 2002; Vickers et al., 2001; Vinay & Moore, 2007b). However, these studies have not reported the percentage information transmission of consonant features in individuals with dead regions separately for individuals having different *fe*.

The present study analyzed consonant feature identification in terms of place, manner and voicing in individuals with and without dead regions. The percentage of input information transmitted for a given feature was determined using Sequential Information Analyses (SINFA) Suite "FIX" software (Mike Johnson, Department of Phonetics & Linguistics, University College London; www.phon.ucl.ac.uk.resource.htm). The consonant features were categorized based upon the classification system given by Ramaswami (1999). The total number of responses in the confusion matrices was based on the responses from 47 ears with dead regions and 14 ears without dead regions.

Confusion matrix was prepared taking into consideration the responses provided by the individuals for the stimuli. The confusion matrices for individuals with and without dead regions are depicted in Tables R.2.9 and R.2.10 respectively. Information transmitted for manner, place and voicing features were separately analyzed for individuals without dead regions and for those with dead regions.

Table R.2.9

Confusion matrix for CV syllables in individuals with dead regions

	p	**b**	**m**	**t**	**D**	**n**	**ṭ**	**ḍ**	**ṇ**	**k**	**g**	**tʃ**	**dʒ**	**j**	**r**	**l**	**v**	**s**	**ʃ**	**h**	**ḷ**
p	31	6	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0
b	7	29	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0
m	2	0	22	2	2	4	1	0	0	3	1	0	1	0	0	0	0	0	1	0	0
t	1	0	0	23	1	1	4	2	0	1	0	0	0	1	1	1	0	0	1	1	1
d	0	1	1	2	26	0	0	1	0	2	0	0	1	1	0	2	0	1	0	2	0
n	0	0	0	0	1	23	1	2	0	0	1	0	3	1	1	2	0	1	0	1	2
ṭ	1	0	0	0	1	1	27	0	0	0	0	2	0	1	1	1	1	0	1	2	1
ḍ	2	0	0	0	1	0	2	24	2	0	0	0	3	1	1	1	0	0	0	0	2
ṇ	0	0	3	1	0	1	0	0	22	0	2	0	0	2	1	1	2	0	2	1	2
k	0	0	0	0	2	0	1	0	2	21	3	0	0	1	1	2	2	1	3	1	0
g	0	1	3	0	0	1	1	1	1	1	22	2	1	1	0	1	1	1	0	0	1
tʃ	3	1	0	1	1	0	1	0	0	0	0	20	4	1	1	0	1	0	1	2	1
dʒ	1	2	0	1	0	2	0	1	1	1	0	0	21	4	0	1	1	1	1	0	0
j	0	0	0	0	0	0	0	0	0	0	0	0	2	25	5	2	3	0	2	0	0
r	0	1	0	0	1	0	1	0	0	2	0	0	3	1	25	5	1	2	0	1	1
l	1	0	1	1	0	1	1	0	1	0	1	0	1	1	2	22	4	1	0	1	0
v	0	0	0	0	0	0	3	0	2	0	0	1	0	2	3	3	23	0	2	1	0
s	2	3	1	0	1	0	0	0	0	3	0	1	2	3	1	2	3	14	2	0	1
ʃ	0	0	0	1	0	2	2	1	3	0	0	0	2	1	2	1	2	3	13	2	3
h	2	0	0	0	0	0	1	0	0	0	0	1	2	0	2	0	1	2	4	21	3
ḷ	0	0	0	2	3	0	0	0	1	3	0	0	0	3	0	1	0	2	1	3	19

Note. x-axis indicates stimulus; y-axis indicates responses.

Table R.2.10

Confusion matrix for CV syllables in individuals without dead regions

	p	**b**	**m**	**t**	**d**	**n**	**ṭ**	**ḍ**	**ṇ**	**k**	**g**	**tʃ**	**dʒ**	**j**	**r**	**l**	**v**	**s**	**ʃ**	**h**	**ḷ**
p	11	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b	1	10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
m	1	0	9	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
t	0	0	1	7	3	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0
d	1	0	1	1	4	0	0	0	1	1	2	0	1	0	0	0	0	0	0	0	0
n	0	0	1	0	1	5	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0
ṭ	1	0	1	0	0	0	7	1	0	2	0	0	0	0	0	0	0	0	0	0	0
ḍ	1	1	0	0	0	0	1	9	0	1	1	0	0	0	0	0	0	0	0	0	0
ṇ	1	1	0	1	0	2	0	1	6	0	1	0	0	0	0	1	0	0	0	0	0
k	0	0	1	0	0	0	0	0	1	11	0	0	0	0	0	0	0	0	0	0	0
g	3	2	0	0	0	1	0	0	1	1	4	0	0	0	0	0	0	0	0	0	0
tʃ	1	1	1	0	0	0	0	1	0	1	2	5	1	1	0	0	0	0	0	0	0
dʒ	0	1	0	0	0	0	0	0	0	0	1	0	9	1	0	0	1	0	1	0	0
j	0	0	0	0	0	0	0	0	0	0	0	1	0	11	1	0	0	0	1	0	0
r	1	0	0	0	0	0	0	0	1	0	1	0	0	1	6	1	1	0	0	1	0
l	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	7	0	0	0	2	1
v	0	1	0	0	0	0	1	0	0	0	1	0	0	1	0	1	7	1	1	0	0
s	0	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0	0	6	1	1	0
ʃ	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	2	6	1	0
h	0	0	0	0	0	0	0	0	1	3	1	0	0	0	0	1	0	0	1	5	1
ḷ	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	1	8

Note. x-axis indicates stimulus; y-axis indicates responses.

2.3.1.1. Information transmission of manner features

Information transmission for manner features in participants with different fe is shown in Figure R.2.5. It may be observed that, information transmission for manner in individuals without dead regions and those with dead regions having *fe* at 3000 and 4000 Hz were similar. However, individuals with dead regions having *fe* at 2000 Hz or lower performed poorer than those without dead regions. This suggests that spectral information below 3000 Hz is important for identification of manner of articulation. It has been reported that F1 transition is one of the important cues for identification of manner feature (Pisoni & Remez, 2005; Von Son & Pols, 1990) and the frequency of the F1 transition varies depending on the constriction of the vocal tract (Kent & Read, 1995).

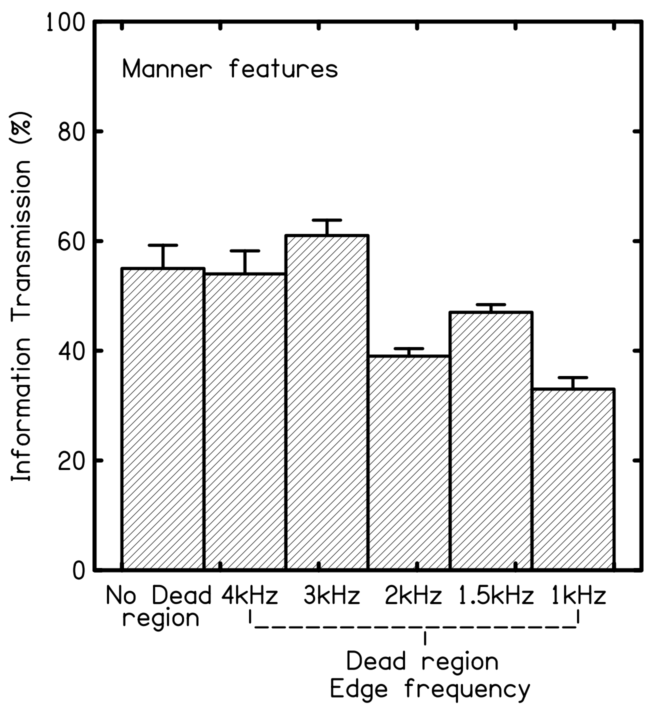

Figure R.2.5. Information transmitted for manner features in individuals with and without dead regions

The confusion matrix was further evaluated to compare the identification of different subcategories of consonants. It was observed that the manner features of nasals, plosives, fricatives and affricates were perceived better in individuals without dead regions when compared to individuals with dead regions. The identification of affricates was comparatively better in individuals having *fe* at 3000 Hz compared to those individuals having *fe* below 3000 Hz. The manner features of tap, lateral and semivowel were perceived similarly in individuals with and without dead regions.

Studies have reported that broadband frequencies play an important role in transmission of nasality and vowel cues (Van Son & Pols, 1996). Geetha et al. (2005) found that nasals and laterals were most affected in individuals with normal hearing when highpass filtered speech was presented. The observation in this study that individuals with high frequency dead regions had poorer score for nasal identification compared to individuals without dead regions and the report by Geetha et al. (2005) suggest that low and mid frequency cues were not sufficient for the identification of nasals. This is probably because the dominant cue for the identification of nasals and laterals requires a broad frequency region (Revoile, Pickett, Holden-Pitt, Talkin & Brandt, 1987).

Previous studies have shown that fricatives and affricates have a higher formant frequency and relatively contain higher energy compared to other speech sounds (Carlyon & Moore, 1984; Smith-Olinde et al. 2004; Stevens, 1985). A fricative has dominant frequency information mostly lying at the high frequencies around 2000 Hz. The dominant cues for identification of plosives lie in the low and mid frequencies (250-500 Hz for /b/; 1000-1500 Hz for /p/ identification) whereas the dominant cues for identification of affricates lie around 2000 Hz (Pisoni & Remez, 2005). Ricketts and

Tharpe, (2005) concluded that high frequency information (above 3000 Hz) can be useful in speech identification for individuals with sensorineural hearing impairment and the cues for affricates have high formant frequencies above 3000 Hz. The finding that individuals with dead regions had poorer identification of fricatives and affricates than those without dead regions and the affricate identification was comparatively better in individuals having *fe* at 3000 Hz compared to those having *fe* below 3000 Hz supports these finding.

2.3.1.1 Information transmission for Place features

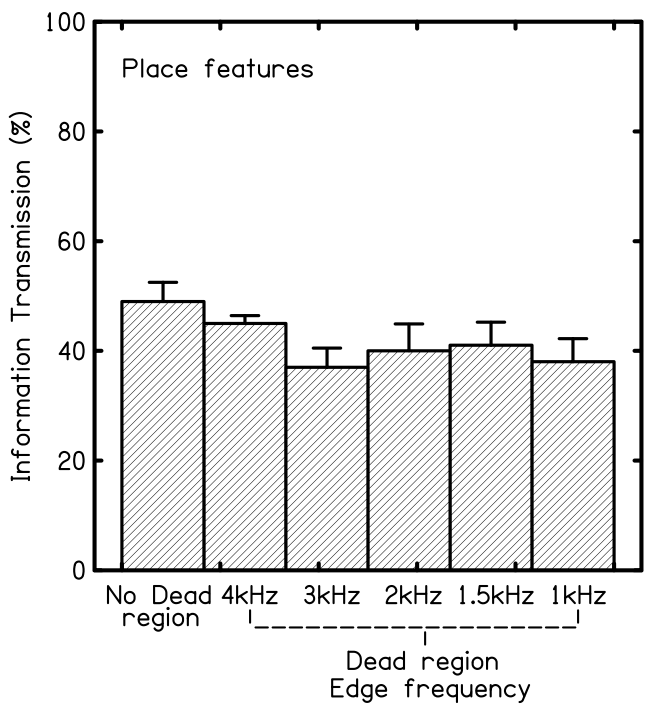

Figure R.2.6. Information transmitted for place features in individuals with and without dead regions

From Figure R.2.6, it may be observed that the information transmission for place features was better in individuals without dead regions when compared to those with dead regions. This suggests that probably individuals without dead regions could extract better consonant information since the neurones were functional in the entire frequency range whereas, in those with dead regions, information transmission was lesser as the neurons were not functional in some of the regions. Information transmission in individuals with dead regions was maximum in individuals having *fe* at 4000 Hz when compared to other individuals. This may be due to the fact that the acoustic identification of place of articulation depends mainly on spectral information (Revoile et al., 1987). The results of the present study indicate that the place errors were more in a majority of the individuals. This may be due to the fact that the cues that are important in the identification of place of articulation are very transient compared to the cues used in manner of articulation (Kent & Read, 1995).

The results of the present study are in consensus with the earlier reports which indicated that place errors are most common in individuals with hearing impairment during CV identification (Bilger & Wang, 1976; Wang et al., 1978). A number of studies (Turner & Cummings, 1999; Turner & Brus, 2001; Van Tasell, 1993; Vickers et al., 2001) hypothesized that severe hearing losses could interfere with the identification of speech, particularly with the identification of place of articulation, which is carried to a large extent by the higher-frequency regions of speech. Geetha et al. (2005) found that place errors were more compared to errors in manner features when high frequency hearing losses with different slopes were simulated in individuals with normal hearing. It has been reported that, for identification of place of articulation, individuals with hearing impairment are unable to use voice onset time, formant transitions or release burst information as cues to place of articulation (Tsui & Ciocca, 2000).

The finding that information transmitted was better in individuals with higher *fe* when compared to those with lower *fe* supports the findings of Wang et al. (1978) who analyzed syllable identification in two different filter conditions – highpass and lowpass. They reported that identification of place feature improved as the lowpass cut-off frequency was increased from 500 Hz to about 5600 Hz and the highpass cut-off frequency was decreased from 4000 to 355 Hz. A consistent trend was not observed in individuals with *fe* lower than 3000 Hz probably because individuals used cues other than spectral cues to understand the consonants.

A comparison among identification of consonants with different places of articulation showed that individuals with and without dead regions perceived the bilabials and labiodentals similarly. The identification of dentals, retroflexes, palatals, velars and glottals were better in individuals without dead regions when compared to those with dead regions. Among the individuals with dead regions, those having *fe* at and below 2000 Hz, had poorer identification of dentals and retroflexes than those having *fe* above 2000 Hz. These findings are probably related to the spectral content of the cues important for their identification.

There is dearth for studies comparing identification of different consonants in individuals with and without dead regions but studies have analyzed speech identification in individuals with sensorineural hearing loss. Geetha et al. (2005) found that the bilabials were most affected in individuals with normal hearing provided with highpass filtered speech. In the sharply sloping condition, for plosives, the confusion was more between /d/ and /b/ followed by /d/ and /g/, and /p/ and /t/. Dubno et al. (1987) have reported that /b/ and /d/ were harder to perceive than /g/ for listeners with a sloping high frequency hearing loss. It has been reported that low and mid frequencies are important for identification of bilabials and labiodentals (around 250-500 Hz for /b/ & /v/; around 1000 Hz for /p/) and can be perceived even when the intensity is relatively low (Miller & Nicely, 1955; Wang et al., 1978). Individuals in the present study had dead regions from *fe* of 1000 Hz and extending above. Hence, probably identification of bilabial and labiodentals did not differ much between individuals with and without dead regions. However, the cut off frequency for the high pass filtered speech used by Geetha et al. (2005) was 750 Hz and the hearing loss for individuals in the investigation by Dubno et al. (1987) started from as low as 250 Hz.

Studies have reported that listeners with severe hearing impairment do not benefit from frequency transition information of retroflexes (Revoile, Pickett & Kozma-Spytek, 1991). Probably, as the degree of hearing loss will usually be greater in individuals with dead region when compared to those without dead regions, the identification of frequency transition was poorer in individuals with dead regions. The cues required for identification of a majority of the dentals and retroflexes lie in the range of 500 Hz -2000 Hz. (Fougeron & Keating, 1997; Klatt, 1987). This may be the reason that individuals having *fe* at and below 2000 Hz showed poorer identification of dentals and retroflexes than those having *fe* above 2000 Hz.

2.3.1.3 Information transmission for voicing features

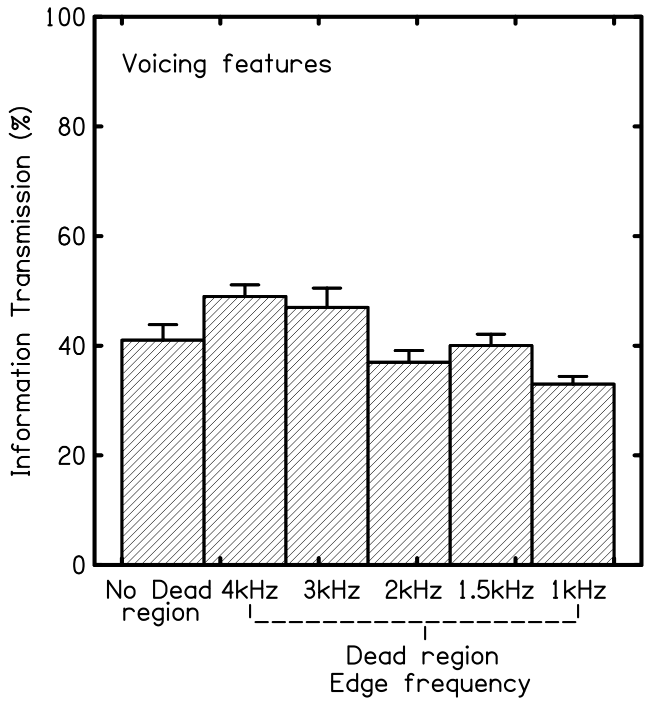

Figure R.2.7. Information transmitted for voicing features in individuals with and without dead regions

The results of the present study showed that the information transmission for voicing almost remained the same in individuals with and without dead regions (Figure R.2.7). This may be attributed to the fact that the spectral information does not a play a major role in identification of voicing in consonants (Hedrick, 1997; Hedrick & Younger, 2001; Kent & Read, 1995; Revoile et al., 1987). The results of the present study are in consensus with the earlier reports (Turner & Brus, 2001). However, these results are in contradiction to that of Geetha et al. (2005) who observed that the voicing errors were more in the gradual sloping condition compared to the sharply sloping condition. The differences in the results observed in the present study may be related to the *fe*. As discussed earlier, individuals in the present study had *fe* at 1000 Hz or higher but the cut off frequency of the high pass filtered speech used by Geetha et al. (2005) was 750 Hz. Identification of consonantal voicing depends mainly on cues related to duration and timing of events (Dubno et al., 1987; Nabelek & Donahue, 1984) and the voice bar which gives cue for identification of voicing lies in the lower frequencies below 500 Hz (Titze, 1994).

To summarize, the present study showed that there was no significant difference in the speech identification scores of threshold matched individuals with and without dead regions but the speech identification scores showed a decreasing trend with decrease in *fe*. The identification of different consonants was differentially affected for individuals with dead regions at various frequencies. The information transfer of consonant feature in terms of place was maximally affected in individuals with dead regions followed by manner of articulation. Identification of the voicing features almost remained similar in individuals with and without dead regions. This is in consensus with the reports in literature which state that identification of place of articulation depends more upon a single parameter of sound – frequency whereas identification of manner contrasts rest on all the parameters of sound- frequency, intensity, timing and spectral information do not play a major role in identification of voicing (Kent & Read, 1995).

3. Speech identification in individuals with dead regions in different amplification conditions

Previous studies have concluded that individuals with dead regions do not benefit from fullband amplification (Vickers et al., 2001; Vinay & Moore, 2007b). The present study analyzed the effects of selective amplification in individuals having dead regions at different *fe*.

3.1. Benefit of amplification

Benefit from amplification was investigated under three different amplification conditions in individuals with dead regions – fullband amplification, amplification up to 1 octave above *fe* and amplification up to the *fe* of the dead region. In individuals without dead regions, the benefit from amplification was studied in full band condition. The individuals were assessed for speech identification abilities using a digital hearing aid with the stimuli delivered through eartips. Speech identification scores for CV stimuli were used to assess the benefit from amplification. Table 3.1 shows the mean and standard deviation of speech identification scores without a hearing aid and with full band amplification in individuals with and without dead regions. It may be observed that the improvement in the mean speech identification scores in fullband condition was more for individuals without dead regions when compared to those with dead regions.

Table R.3.1

Mean and standard deviation (SD) for speech identification scores for CV stimuli for individuals with and without dead regions in unaided and fullband amplification condition

Groups	**Unaided**		**Fullband**	
	Mean	**SD**	**Mean**	**SD**
Dead region	7.56	2.97	9.27	3.10
No dead region	10.04	2.43	12.83	2.71

Independent Sample t-test revealed a significant difference in the speech identification scores in fullband condition for individuals with and without dead regions ($t=7.52$; $p<0.001$). The results of the present study are in consensus with the earlier studies which report that individuals without dead regions benefit more from fullband amplification when compared to individuals with dead regions (Vickers et al., 2001; Vinay & Moore, 2007b).

The necessity of providing high frequency amplification to individuals with high frequency hearing loss has been debated for a long time. Previous studies have shown that providing gain in the high frequencies may fail to improve speech identification or even result in a decrease in performance in some of the individuals (Ching et al., 1998; Hogan & Turner 1998; Murray & Byrne 1986; Rankovic 1991; Skinner 1980; Turner & Cummings 1999; Vickers et al., 2001; Wang & Bilger, 1973). Murray and Byrne (1986) indicated that individuals with moderately severe to severe losses may not always benefit from high frequency amplification. In the present study, full band amplification improved the mean speech identification scores in individuals with dead regions but the improvement seen was lesser when compared to that observed in individuals without dead regions which indicate that the individuals with dead regions cannot utilize high frequency information to the same extent as those without dead regions.

Further analyses were carried out to compare speech identification scores in different amplification conditions in individuals with dead regions. The data from males and females were merged as the Independent Sample t-test revealed no significant difference between the two groups for the three amplification conditions ($t = 1.18$; $p>0.05$ for fullband condition; $t = 0.37$; $p>0.05$ for one octave above *fe* condition; $t = 1.56$; $p>0.05$ for amplification up to *fe* condition). The mean and standard deviation values for speech identification scores for the three amplification conditions are depicted in Table R.3.2. A repeated measure ANOVA was carried out with age and degree of hearing loss as between subject factors and speech identification scores in different amplification conditions as within subject factors. Results indicated that there was no significant effect of age {$F (1, 91) =3.06$; $p>0.05$} or degree of hearing loss {$F (3, 91) =1.6$; $p>0.05$} on the speech identification scores but there was a main effect of amplification condition {$F (1, 91) =36.23$; $p<0.001$}. There was no significant interaction effect between age and degree of hearing loss {$F (3, 91) =0.43$; $p>0.05$} on the speech identification scores in different amplification conditions. The results of Bonferroni posthoc test revealed that there was a highly significant difference between the speech identification scores in the amplification up to one octave above *fe* and fullband amplification ($p<0.001$); between one octave above *fe* and up to *fe* ($p<0.001$) and between fullband amplification and amplification up to *fe* ($p<0.001$) condition.

Table R.3.2

Mean and standard deviation (SD) values for speech identification scores (SIS) in different amplification conditions

Amplification conditions	Mean SRS	SD
Fullband	9.58	2.94
1 octave above *fe*	11.20	2.88
Edge frequency	7.26	2.74

These results are in consensus with the earlier study by Skinner (1980) who suggested that the degree and/or configuration of hearing loss could not be used to determine individuals who are likely to benefit from high-frequency amplification from those who do not. However, the presence of dead regions and the estimation of the *fe* were not determined by Skinner (1980). Earlier studies that have been carried out to investigate the effects of different cut-off frequencies on the speech identification scores in individuals with and without dead regions have reported equivocal results. Vinay and Moore (2007b) reported that individuals with low frequency dead regions could make effective use of amplification provided up to about 0.57*fe*. It was concluded that amplification of frequency regions below 0.57*fe* had deteriorating effects on speech identification abilities. Similarly Vickers et al. (2001) observed that in individuals with high frequency dead regions scores tended to increase with increasing lowpass cutoff frequency up to 1.5 f_e to 2 f_e whereas for individuals without dead regions, performance improved progressively with increasing cutoff frequency. These investigators concluded that providing fullband amplification had deleterious effect on the speech identification scores in individuals with dead regions. Contrary to these reports, Mackersie, Crocker and Davis (2004) concluded that, in quiet and low levels of noise conditions, the unfiltered scores were better than the filtered scores and there was no significant difference between the scores in individuals with and without dead regions. However, in the presence of high levels of noise, individuals without dead region performed significantly better than individuals with dead regions.

The results of the present study reinforce the consensus that the mean speech identification scores is maximum when amplification is provided up to one octave above *fe* compared to the other two conditions. However the results did not reveal any deleterious effect when fullband amplification was provided compared to the unaided condition. The present study included more heterogeneous group of individuals in terms of *fe* of the dead region and severity of hearing loss when compared to the earlier studies reported in literature (Vickers et al., 2001; Baer et al., 2002). Another major difference between the present study and the earlier studies is that amplification was provided using a hearing aid in the present study whereas in a majority of the earlier studies (Vickers et al., 2001; Vinay & Moore, 2007b) amplification was provided using the 'Cambridge formula' and the output was delivered through a headphone at various cut-off frequencies and not through a hearing aid. Amplification provided in the previous studies through 'Cambridge formula' is intended to provide equal loudness/ERB_N over the speech frequency range from 500 to 4000 Hz with a bandwidth of around 7500 Hz in the fullband condition (Vickers et al., 2001; Vinay & Moore, 2007b). However, the digital hearing aid used in the present study typically had a frequency range consisting of lower frequency limit of 120 Hz up to a higher frequency limit of 6400 Hz and started tapering after 6400 Hz with no useful amplification above 8000 Hz. The differences in results could be due to these methodological variations.

3.2. Effect of amplification conditions in individuals with different fe

There is a dearth in literature regarding effect of amplification conditions on the speech identification abilities in individuals having different *fe* of the dead regions. In the present study individuals were classified based on the *fe* of the dead regions and the effect of selective amplification was analyzed separately for each of these groups. The speech identification scores under three different amplification conditions for individuals with different *fe* are shown in Table R.3.3. From the table it is evident that the speech identification scores were maximum when amplification was provided up to one octave above the *fe* for all the groups. Repeated measure ANOVA was carried out for each group to know if there was a significant effect of amplification conditions on speech identification scores. Results revealed a significant effect of the amplification condition on the speech identification scores in individuals having different *fe* {$F(1, 21)=27.06$; $p<0.001$ for 1000 Hz; $F(1, 15)=10.37$; $p<0.01$ for 1500 Hz; $F(1, 26)=7.52$; $p<0.05$ for 2000 Hz; $F(1, 16)=9.63$; $p<0.01$ for 3000 Hz and $F(1, 16)=6.77$; $p<0.05$ for 4000 Hz}.

Table R.3.3

Mean and standard deviation (in brackets) for speech identification scores for CV stimuli for individuals with different fe in different amplification conditions

	Amplification conditions			
Edge frequency (Hz)	**Unaided**	**Fullband**	**One octave above Edge Frequency**	**Edge frequency**
1000	7.5 (3.44)	8.91 (2.22)	10.73 (2.23)	6.23 (2.72)
1500	6.57 (3.11)	8.37 (2.7)	10.13 (3.18)	5.63 (1.71)
2000	7.9 (2.23)	9.41 (2.99)	11.52 (3.33)	7.52 (2.42)
3000	8.0 (3.46)	10.53 (3.08)	12.18 (2.21)	7.88 (2.76)
4000	7.75 (3.11)	10.88 (3.26)	11.35 (2.04)	9.12 (2.85)

Table R.3.4

'p' values for groups with different fe among different amplification conditions

Amplification conditions	**Edge frequencies (Hz)**				
	1000	**1500**	**2000**	**3000**	**4000**
One octave above fe *& fullband*	<0.01	<0.05	<0.001	>0.05	>0.05
One octave above *fe* & *fe*	<0.001	<0.01	<0.001	<0.001	<0.05
Fullband & *fe*	<0.001	<0.05	<0.05	<0.05	>0.05

Results of the Bonferroni posthoc test are depicted in Table R.3.4. Significantly poorer scores when amplification was provided only till *fe* when compared to other two amplification conditions indicate that the individuals with high frequency dead regions were able to use information available in frequencies of dead region. However scores were significantly better when amplification was provided till one octave above *fe* when compared to full band amplification. This pattern was true for individuals having *fe* at 1000, 1500 and 2000 Hz. This suggests that these individuals were not able to make effective use of amplification in the full band condition. Previous studies have shown that, in case of a high frequency dead region, amplified high frequency components of speech stimuli are perceived by the neurons that are tuned to the lower frequencies. Thus there will be information 'overload' in the neurons that are tuned to lower frequencies. There is evidence to support this information from studies involving simulation of hearing loss and/or cochlear implant processing (Shannon, Zeng & Wygonski, 1998). If the information that falls in the area of a dead region is sufficiently amplified to make them audible, then that information will be detected and transmitted by the neurons that are tuned to different frequencies. Thus there may be a possibility that individuals with dead regions obtain some benefit when amplification is provided up to one octave above the *fe*. This may be due to the phenomenon of off-frequency listening (Patterson & Nimmo-Smith, 1980). However, when there is a mismatch between the frequencies of speech component and the place where they are detected, the temporal decoding mechanisms required to analyze those speech components may not operate effectively (Miller, Schilling, Franck & Young, 1997; Sachs & Young, 1980). Providing full band amplification may probably lead to this mismatch by amplifying higher frequencies. Thus, due to the combined effect of frequency-place mismatch and ineffective temporal coding, the benefit derived from full band amplification may be lesser when compared to benefit derived when amplification is provided up to one octave above *fe* of the dead region. Thus the benefit obtained from amplification in individuals with dead regions depends upon the degree of cochlear damage which determines the *fe* of the dead region and the extent of amplification provided to these individuals.

There was no significant difference between fullband amplification and amplification up to one octave above the *fe* for individuals having *fe* at 3000 and 4000 Hz. It was also observed that the difference between the speech identification scores in fullband and amplification up to *fe* condition was lesser in individuals having *fe* at 4000 Hz compared to individuals having *fe* at 3000 Hz. This may be because, the frequency response of the hearing aid tapered down after 6400 Hz and did not provide any useful amplification above 8000 Hz. Hence, amplification provided in full band condition was similar to that of one octave above *fe* condition.

3.2.1 Consonant identification with fullband amplification condition

The stimulus-response matrix for CV syllables in fullband condition for all individuals is depicted in Table R.3.5. The total number of responses in confusion matrices was based on responses from 102 ears with dead regions. The results depicted in Figure R.3.1 indicate that in a majority of the groups, information transfer was least for place features and highest for manner features with fullband amplification. However, for individuals with *fe* at 1000 Hz, information transmitted for voicing was more than manner. With fullband amplification, information transmitted for place features was more in individuals having *fe* at 3000 and 4000 Hz with a gradual decrease as *fe* decreased below 3000 Hz. Similar trend was observed for transmission of manner features also, but the reduction observed with decrease in *fe* was more drastic. In terms of voicing feature, information transmission was slightly higher for individuals having *fe* at 4000 Hz, however transmission scores were almost the same for individuals having other *fe*. The results of present study indicated that transmission of manner, place and voicing showed improvement in fullband amplification condition irrespective of the *fe*. Further inspection of data indicated that information transmission for manner and place was more for individuals having *fe* at 3000 and 4000 Hz compared to individuals having *fe* at other frequencies but no such trend was observed for information transmission of place and voicing.

Table R.3.5

Confusion matrix for CV syllables in fullband amplification condition

	p	b	m	t	d	n	ṭ	ḍ	ṇ	k	g	tʃ	dʒ	j	r	l	v	s	ʃ	h	ḷ
p	47	5	2	2	1	0	2	0	0	3	1	1	0	1	0	1	0	0	0	1	1
b	4	51	3	1	4	2	0	2	0	1	2	0	1	0	1	0	0	0	0	0	0
m	3	4	33	1	1	3	1	0	2	0	1	0	1	1	0	1	0	0	0	1	2
t	2	2	1	39	5	1	3	2	1	3	0	1	0	0	2	0	1	0	0	0	0
d	4	4	0	5	36	0	2	3	0	0	5	1	0	2	0	2	0	0	0	0	1
n	0	1	3	2	1	30	1	0	6	1	2	0	2	0	1	4	2	0	0	1	0
ṭ	1	0	0	3	0	2	36	5	1	3	0	2	1	1	0	1	0	0	1	0	0
ḍ	2	2	1	1	7	1	1	38	1	1	2	1	3	0	1	1	0	0	0	0	1
ṇ	0	0	4	1	0	5	0	3	26	1	1	0	0	2	0	1	2	0	0	0	5
k	6	2	1	2	1	0	2	1	1	37	4	1	1	0	0	0	1	1	0	2	0
g	0	1	0	0	4	1	1	3	1	5	33	1	4	1	0	2	0	0	0	1	1
tʃ	2	0	1	3	2	0	2	1	0	1	2	26	3	2	1	0	1	1	2	0	2
dʒ	0	3	1	0	4	1	0	2	1	0	1	7	28	4	0	2	1	0	1	1	0
j	0	0	0	1	0	0	1	0	0	1	0	0	2	30	3	2	2	0	0	1	2
r	1	0	1	0	2	1	0	1	0	0	2	1	3	1	26	4	0	1	0	2	3
l	0	1	0	2	0	0	1	0	1	0	0	1	0	3	4	36	5	0	2	1	4
v	4	2	1	2	1	1	0	0	0	2	1	0	1	2	3	2	23	0	0	2	1
s	1	0	2	3	1	0	1	0	0	1	0	4	3	0	1	1	2	27	8	4	0
ʃ	0	1	0	1	3	0	0	0	1	0	2	6	4	1	0	2	0	7	29	3	1
h	1	0	1	4	0	0	2	0	0	2	1	1	0	1	1	2	3	1	1	23	2
ḷ	0	1	0	1	1	2	0	0	1	1	0	0	1	2	0	4	2	1	0	2	23

Note. x-axis indicates stimulus; y-axis indicates responses.

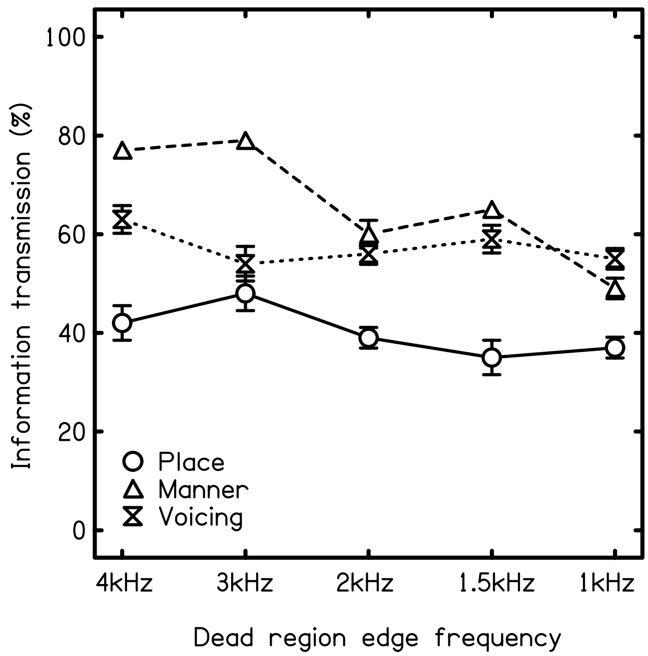

Figure R.3.1. Information transmitted in terms of place, manner and voicing features in fullband amplification conditions in individuals with dead regions

The results of the present study are in consensus with the earlier reports (Gordon-Salant, 1984; Turner & Brus, 2001; Vickers et al., 2001; Vinay & Moore, 2007b). Vickers et al. (2001) observed that the percentage of information transmitted was lowest for place of articulation in individuals with high frequency dead regions and they did not benefit from high frequency amplification with various low pass cut-off frequencies. Vinay and Moore (2007b) observed similar results in individuals with low frequency dead regions when amplification was provided at various high pass cut-off frequencies. Turner and Brus (2001) suggested that the main difficulty of individuals with hearing impairment in using amplified speech was due to the poor ability to perceive the place and the manner of articulation of speech sounds. However, none of these studies have analyzed the effect of amplification condition in individuals with different *fe*.

The results obtained in the present study for individuals with different *fe* can be explained in terms of acoustic cues for speech identification and the effect of dead regions on it. As discussed in the previous section, frequency is the most important parameter for identification of place of articulation whereas all features of sound are important for identification of manner contrasts. Probably individuals with *fe* at 2000 Hz and lesser could not make effective use of the high frequency amplification provided to them and hence information transmitted for place and manner features was lower than those with *fe* at 3000 and 4000 Hz. The results also indicate that increased audibility at lower frequencies, where there were no dead regions, did not completely compensate for their hearing loss in these individuals. In fullband amplification condition, the information transmitted for voicing features was same across individuals having different *fe* probably because spectral information contributes minimally for identification of voicing features.

The information transmitted for various place features in individuals with dead regions in fullband condition is depicted in Figure R.3.2. Results indicated that all place features were perceived better when fullband amplification was provided compared to the unaided condition in individuals with different *fe*. It was observed that the improvement in identification of bilabials and labiodentals was almost similar for individuals with *fe* at 1000 and 1500 Hz, probably since most of the frequency information required for identification of bilabial and labiodentals identification lies in the low to mid frequencies (Revoile, Pickett, Holden-Pitt, Talkin & Brandt, 1987). However, the identification of labiodentals deteriorated for individuals having *fe* at and above 2000 Hz.

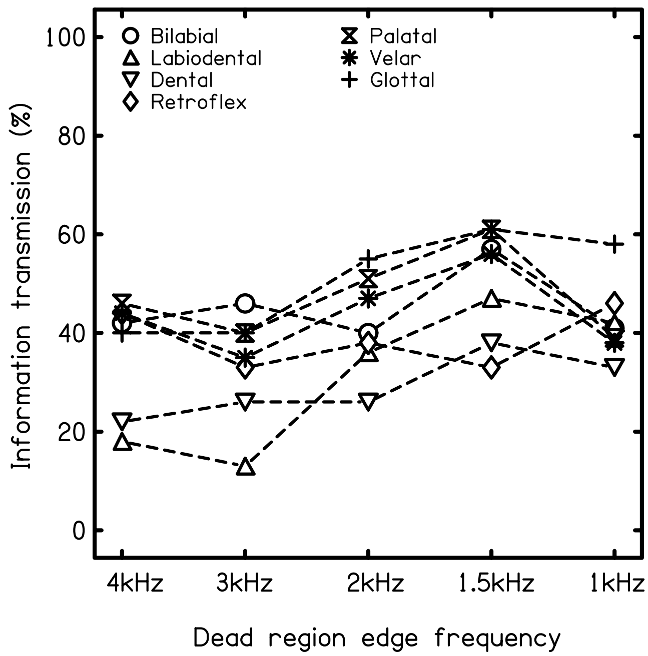

Figure R.3.2. Information transmitted for different place features in fullband amplification conditions in individuals with dead regions

It was observed that identification of dentals was better for individuals having *fe* above 2000 Hz compared to those having *fe* below 2000 Hz. Previous studies have shown that the identification of /p/-/t/ contrast by listeners with hearing impairment can be influenced by audibility (Ohde & Stevens, 1983) and higher presentation levels resulted in greater identification of dental features. The information transmission for retroflex was almost same for individuals having different *fe*. For glottal identification, individuals having *fe* at 2000, 3000 and 4000 Hz benefited more from fullband amplification compared to individuals having *fe* at 1000 and 1500 Hz. These results are in consensus with the earlier reports regarding frequency spectrum required for glottal identification (Revoile et al. 1987; Wang et al. 1978). The highest information transmission observed for bilabials, labiodentals, dentals, palatals, velars and glottal for individuals having *fe* of 3000 Hz may be speculated due to the fact that individuals with a having a lower *fe* could not make use of the high frequency amplification provided to them and probably these individuals had greater degree of loss.

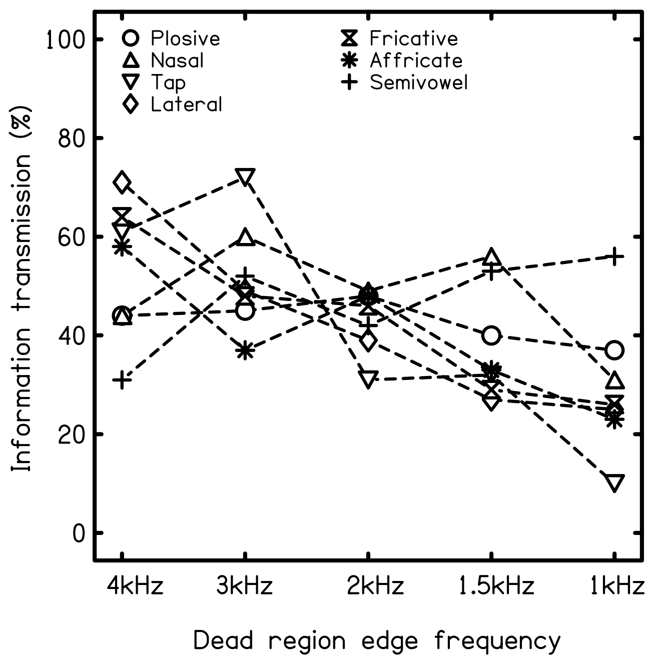

Figure R.3.3. Information transmitted for different manner features in fullband amplification conditions in individuals with dead regions

Figure 3.3 shows that the information transmission was comparatively more with fullband amplification when compared to the unaided condition for all the manner contrasts. The information transmission for plosives and nasals was lesser for individuals having *fe* at 1000 Hz compared to those having *fe* greater than 1000 Hz. Previous studies have reported that low frequencies play an important role in transmission of nasality and vowel cues (Revoile et al., 1987). The information transmission for taps increased drastically for individuals having *fe* at 3000 Hz and above. The information transmission for laterals, fricatives and affricates was maximum for individuals having *fe* at 4000 Hz and the scores almost gradually decreased as the *fe* decreased. The higher frequencies help in providing frication cues (Carlyon & Moore, 1984; Smith-Olinde, Besing & Koehnke, 2004). Fricatives, affricates and some of the alveolar sounds have high formant frequency and thus the transition cues from a consonant to a vowel depend upon the transition frequency difference between a vowel and a consonant (Hedrick, 1997; Hedrick & Carney, 1997). The results of the present study showed that identification of fricatives and affricates was better in individuals having *fe* at 4000 Hz.

Thus, the results indicated that dead regions at different frequencies might differentially affect the identification of different consonants. The benefit obtained from fullband amplification compared to unaided condition depends upon the extent of dead regions. Probably individuals with a higher *fe* were able to make effective use of the high frequency amplification when compared to individuals having a lower *fe* since individuals with a higher *fe* may have more surviving neurones in the higher frequencies compared to individuals having a lower *fe*.

3.2.2. Consonant identification with amplification up to one octave above fe

The stimulus-response matrix for CV syllables in amplification up to one octave above *fe* condition for all individuals is depicted in Table R.3.6. The total number of responses in confusion matrices was based on responses from 102 ears with dead regions. The results of present study indicated that providing amplification up to one octave above the *fe* resulted in improvement of information transmission for overall place features (Figure R.3.4) when compared to unaided condition in these individuals. It was observed that maximum benefit was obtained from individuals having *fe* at 2000 and 3000 Hz. For individuals having *fe* at 4000 Hz, there was no considerable improvement in consonant identification compared to fullband condition. The improvement in transmission for manner features observed for individuals with dead regions having higher *fe* at 3000 and 4000 Hz was relatively lesser than observed for individuals having a lower *fe* at 1000, 1500 and 2000 Hz. However, within the amplification condition, the overall scores were almost the same across all individuals having different *fe*. The information transmission for manner features was higher for individuals having *fe* at 1000, 1500, 2000 and 3000 Hz than compared to the unaided condition, the identification of manner by individuals having *fe* at 4000 Hz being slightly lesser when compared to those having other *fe*. There was an improvement observed in identification of voicing features when compared to unaided condition. The information transmitted for voicing feature was highest for individuals having *fe* at 4000 Hz and lowest for those having *fe* at 1000 Hz. The information transmitted for voicing features was almost similar to that obtained for place of articulation but was lesser than that observed for manner features.

Table R.3.6

Confusion matrix for CV syllables in amplification up to one octave above fe condition

	p	**b**	**m**	**t**	**d**	**n**	**ṭ**	**ḍ**	**ṇ**	**k**	**g**	**tʃ**	**dʒ**	**j**	**r**	**l**	**v**	**s**	**ʃ**	**h**	**ḷ**
p	55	10	2	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0
b	5	53	3	1	4	2	0	1	0	1	0	0	1	0	0	1	0	0	0	1	0
m	4	3	47	0	2	0	1	1	3	1	2	0	0	1	0	0	1	0	0	0	0
t	4	1	0	48	3	1	2	3	0	2	1	1	0	0	0	1	0	0	0	1	1
d	1	3	2	5	49	2	1	2	0	2	2	0	1	0	1	0	1	1	0	0	0
n	0	0	3	1	1	38	1	0	5	1	0	1	0	0	0	2	0	0	0	0	2
ṭ	1	2	0	3	1	1	43	2	2	1	1	0	1	0	0	0	0	0	0	1	1
ḍ	0	1	1	1	3	3	4	39	2	1	3	1	0	0	0	1	0	0	0	0	0
ṇ	0	0	3	1	1	2	1	1	34	1	1	0	1	0	0	0	0	0	0	0	4
k	3	4	0	2	2	1	2	1	0	40	6	2	1	2	1	0	1	0	0	1	0
g	1	2	1	1	1	0	0	2	1	4	38	1	3	0	1	1	0	0	1	1	0
tʃ	0	0	1	2	0	1	1	0	1	0	3	31	9	4	1	0	0	2	1	2	1
dʒ	0	2	0	1	2	1	0	1	0	2	4	5	33	1	0	0	1	1	0	0	0
j	1	0	1	0	0	0	2	1	0	1	1	0	2	37	3	2	4	0	1	0	1
r	2	1	0	1	0	1	0	0	0	1	0	0	0	1	36	5	4	0	0	1	1
l	1	0	1	1	1	0	1	0	1	0	2	0	1	3	4	37	3	0	0	1	3
v	6	2	1	2	2	0	1	0	2	3	0	1	0	2	3	2	30	0	0	2	1
s	1	0	0	4	1	1	0	1	0	1	0	3	2	1	0	0	1	25	5	1	0
ʃ	0	2	1	1	0	0	1	0	1	0	1	4	3	1	1	1	2	6	23	0	1
h	2	2	0	1	1	0	0	1	0	2	0	0	0	2	1	3	2	1	0	34	3
ḷ	0	0	1	1	0	1	0	1	4	2	1	1	0	1	2	7	1	0	0	1	34

Note. x-axis indicates stimulus; y-axis indicates responses.

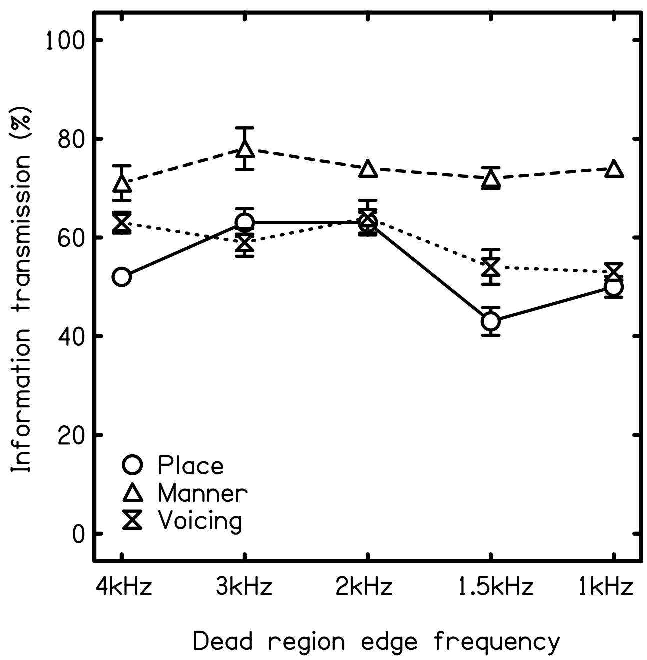

Figure R.3.4. Information transmitted in terms of place, manner and voicing features in amplification up to one octave above *fe* condition in individuals with dead regions

These results show that the individuals were able to make effective use of amplification up to one octave above the *fe.* The results obtained for identification of place and manner features are in consensus with the earlier reports (Vickers et al., 2001). The benefit observed in individuals having *fe* at 2000 Hz was probably due to the frequency response of the hearing aid used in the present study that started tapering around 6400 Hz and deteriorated completely by about 8000 Hz. Hence these individuals could utilize important speech frequency information provided up to 4000 Hz. The reason for individuals having *fe* lesser than 4000 Hz obtaining benefit from amplification may be because these individuals had poorer threshold at low and mid frequencies also and hence did not show much improvement. The results obtained for voicing feature in the present study are in contradiction to the results obtained by Vickers et al. (2001) in individuals with high frequency dead regions. It may be noted that Vickers et al. (2001) assessed speech identification abilities in terms of consonant features in English language. However, the present study was carried out using the native Kannada language using different amplification conditions. Thus, the differences between the two languages in terms of the voicing features and phonemic content may be responsible for the contradictory results in individuals with high frequency dead regions. It has been reported that distinction between voiced and unvoiced is more prominent in English language due to the presence of aspiration of plosives present in the initial position and due to the presence of formant cut back (Savithri, 1996).

The results of the present study indicated that maximum improvement for the identification of place features of bilabials, labiodentals, dentals, palatals and velars occurred for individuals having *fe* at 2000 and 3000 Hz (Figure R.3.5). It was observed that individuals with *fe* at 4000 Hz did not obtain much benefit in terms of information transmission when amplification was provided up to one octave above the *fe*. However, the improvement in identification of place of articulation of retroflex was higher for individuals having *fe* at 2000, 3000 and 4000 Hz. The information transmission for glottal was relatively higher for all individuals having different *fe* compared to other place features.

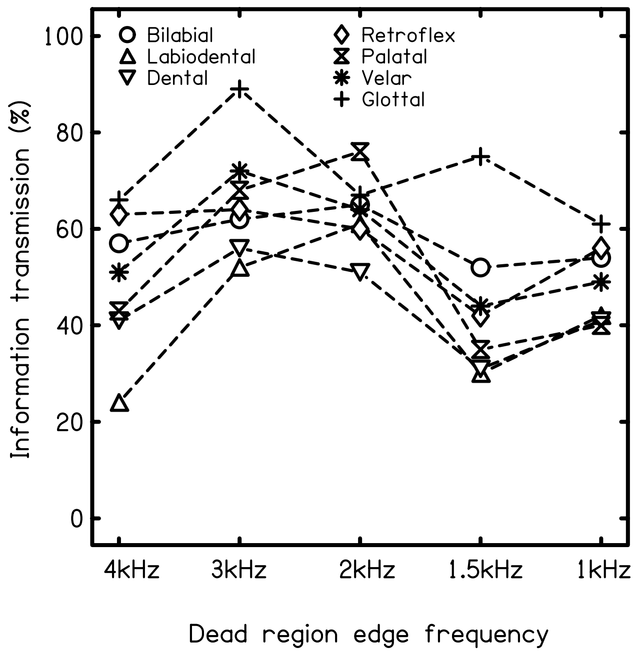

Figure R.3.5. Information transmitted for different place features in amplification up to one octave above *fe* condition in individuals with dead regions

In terms of the overall manner features the improvement was maximum when amplification was provided up to one octave above the *fe* compared to the other amplification conditions and the unaided condition (Figure R.3.6). It was observed that improvement for plosives was maximum for individuals having *fe* at 2000 Hz. For identification of nasals, it was observed that the information transmission was highest for individuals having *fe* at 3000 Hz.

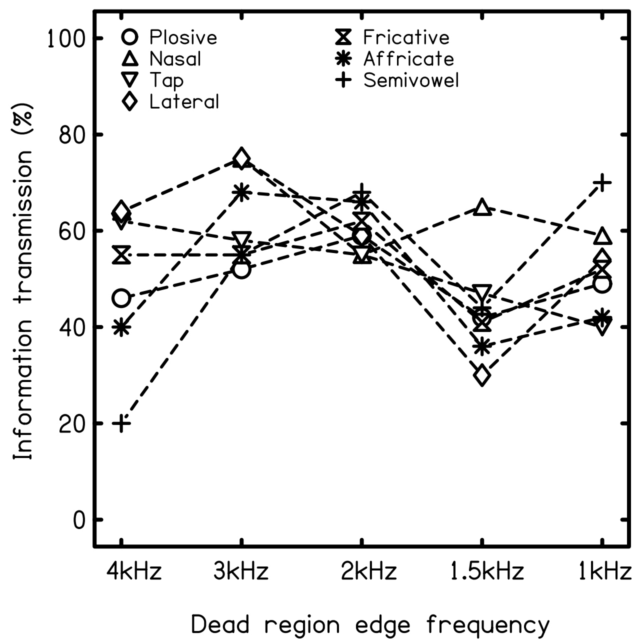

Figure R.3.6. Information transmitted for different manner features in amplification up to one octave above *fe* condition in individuals with dead regions

Providing amplification up to one octave above for individuals having *fe* at 1000, 1500 or 2000 Hz may not provide adequate audibility in the higher frequencies and the results of the present study reinforce earlier results suggesting that the information in lower and mid frequencies is not sufficient for identification of nasals. Individuals with *fe* at 4000 Hz obtained reasonably good information transmission for nasals, however, the transmission was relatively lesser compared to individuals having *fe* at 3000 Hz probably because they missed low frequency information. The improvement in identification of nasals was comparatively more when amplification was provided up to one octave above *fe* when compared to fullband amplification and unaided condition.

The results of the present study report that the information transmission for tap, laterals and fricatives was reasonably good for individuals having *fe* at 2000, 3000 and 4000 Hz when amplification was provided up to one octave above *fe*. There was only slight improvement in the identification scores for affricates when amplification was provided one octave above *fe* of the dead region compared to the information transmission observed in the fullband condition. However, within the amplification condition, the information transmission for affricates and semivowels were better for individuals having *fe* at 2000 and 3000 Hz compared to individuals having other *fe* and was least for individuals having *fe* at 4000 Hz.

The results of the present study are in consensus with the earlier reports, which conclude that frequency information and audibility are important for consonant identification (Kent & Read, 1995; Revoile et al., 1987). The reason for observing maximum improvement in the identification of place features of bilabials, labiodentals, dentals, palatals and velars in individuals having *fe* at 2000 and 3000 Hz may be due to the fact that individuals would have obtained adequate amplification required for the consonant identification of these features. Moore (2001) has reported that the bilabial and dental identification in individuals with dead regions may be related to increased thresholds leading to reduced audibility in these individuals. Hedrick and Younger (2007) reported that usefulness of formant transition cues for voiceless stop consonants depended on the listening condition and degree of hearing loss. It was observed that hearing loss reduced the effectiveness of consonant identification. The improvement in the identification of plosives may be because most of the frequency information for plosives lie in low to mid frequencies and that providing fullband amplification above the mid frequencies may cause overamplification and may deteriorate the identification of plosives because of information overload combined with reduced hearing sensitivity in the low frequencies in these individuals (Hedrick & Jesteadt, 1996; Hedrick & Younger, 2001). The reason for no improvement observed in the identification of nasals in individuals having a higher *fe* at 4000 Hz may be due to the fact that most frequency information required for identification of nasals lie below 4000 Hz and providing amplification above 4000 Hz may not be useful. Previous studies have examined the effect of frequency information spectrum for fricatives in individuals with hearing impairment (Hedrick & Carney, 1997). They concluded that formant frequencies information did not provide cue for fricative identification in individuals with hearing impairment and also that, the cues reduced as the severity of hearing loss increased.

The reason for individuals with *fe* at 4000 Hz showing an improvement in the place and manner features may be due to the high frequency information obtained from amplification of frequencies above 4000 Hz required for identification of high frequency consonants such as fricatives that has dominant energy at the higher frequencies (Revoile et al., 1987). These results are in consensus with the earlier reports by Vickers et al. (2001) that showed that providing high frequency amplification even above 4000 Hz for individuals having *fe* at 4000 Hz might be beneficial when lowpass cut-off frequency was increased. The results are in consensus with the study by Wang et al. (1978), which reported that the identification of manner feature such as frication, sibilants and stridents improved as the lowpass cut-off frequency was increased from 500 Hz to about 5600 Hz. The reason for better identification of affricates and semivowels in individuals having *fe* at 2000 and 3000 Hz may be because most of the dominant information lies in the mid to high frequencies for affricate identification and in the mid frequencies for identification of semivowels. Hence providing amplification above 4000 Hz was not beneficial for these individuals. Several studies suggest that hearing loss may result in a frequency-specific deficit in the contribution of speech information (Ching et al., 1998; Turner & Cummings, 1999).

Some of the previous studies carried out conclude that high-frequency amplification may not always be beneficial due to considerable inter-subject variability among these individuals. It was shown that some individuals were able to use high-frequency information, some showed no benefit, and others showed a decrease in performance (Baer et al., 2002; Vickers et al., 2001). However, in the present study, individuals having a *fe* at 1000 Hz or 1500 Hz and extending upwards had difficulty in the identification of fricatives and affricates which has dominant frequency information in the higher frequencies. The identification of semivowels was better when amplification was provided beyond the *fe* for individuals having different *fe* except at 4000 Hz, since these individuals could utilize the effective frequency information.

From the results, it is evident that individuals with dead regions were able to utilize the frequency information up to one octave above the *fe* and the results indicate that selective amplification may be more beneficial compared to fullband amplification and unaided condition in these individuals.

3.2.3. Consonant identification with amplification up to fe

The stimulus-response matrix for CV syllables in amplification up to *fe* condition for all individuals is depicted in Table R.3.7. The total number of responses in the confusion matrices was based on the responses from 102 ears with dead regions. The results of the present study report that information transmission for place features was least for all the individuals when amplification was provided up to the *fe* of the dead region compared to the other two amplification conditions (Figure R.3.7). Similar to other conditions, even in this condition, the information transmission for manner features was maximum followed by voicing and place features. It was also observed that the information transmission for place features was poorer compared to the other two amplification conditions and the unaided condition in individuals having *fe* at all frequencies. The information transmission for place features reduced as the *fe* decreased. It was observed that the information transmitted for place features was lesser for individuals having *fe* at 1000 and 1500 Hz compared to those having *fe* at and above 2000 Hz. In individuals with higher *fe,* the information transmitted for manner feature was more than individuals having lower *fe*. Individuals obtained poorer scores for manner features when amplification was provided up to the *fe* of dead region compared to the other two conditions and unaided condition. The information transmission for voicing feature almost remained constant for individuals having *fe* at 2000, 3000 and 4000 Hz, but reduced for those having *fe* at 1000 and 1500 Hz.

Table R.3.7

Confusion matrix for CV syllables in amplification up to the fe condition

	p	b	m	t	d	n	ṭ	ḍ	ṇ	k	g	tʃ	dʒ	j	r	l	v	s	ʃ	h	ḷ
p	43	14	3	3	3	0	2	0	0	1	1	0	0	0	0	0	0	0	0	0	0
b	9	44	1	2	1	1	0	1	0	1	0	0	1	0	2	0	3	0	0	2	1
m	2	1	27	3	2	4	1	3	5	2	1	2	0	1	1	1	0	0	0	0	0
t	4	5	2	31	3	3	0	1	0	4	0	1	1	1	0	0	1	0	0	0	0
d	1	2	1	1	28	2	1	5	2	3	2	1	4	0	1	2	0	1	0	1	3
n	3	4	3	2	1	27	4	4	3	2	1	3	0	2	0	2	1	0	0	3	1
ṭ	5	2	4	6	2	1	30	7	2	1	1	0	1	1	1	0	0	0	0	1	1
ḍ	1	3	0	4	5	0	2	24	1	0	3	1	1	1	2	1	1	0	1	1	1
ṇ	2	2	3	1	1	5	1	2	20	2	3	0	4	1	1	2	3	0	0	4	5
k	6	1	0	3	0	1	2	2	1	29	5	0	0	3	2	4	2	1	0	0	3
g	3	4	1	1	2	1	0	1	1	7	20	2	1	1	1	1	1	0	0	2	0
tʃ	4	5	2	6	3	1	2	3	1	3	2	20	5	2	0	1	1	1	1	3	4
dʒ	7	9	2	1	2	2	1	0	2	1	0	1	22	4	2	2	0	0	0	2	2
j	0	2	3	1	2	1	2	1	3	1	1	0	2	22	4	2	5	2	1	0	3
r	5	1	2	4	4	1	1	0	1	0	3	0	1	2	19	6	4	0	0	1	1
l	2	1	1	1	2	3	3	1	0	2	0	0	0	5	6	26	3	0	0	0	5
v	6	2	0	3	1	0	4	3	2	0	1	2	2	0	2	3	21	1	0	2	0
s	4	3	2	2	2	1	2	2	3	2	2	4	3	4	2	1	1	16	4	1	3
ʃ	5	3	2	3	1	0	1	0	0	1	0	0	1	0	1	1	0	3	14	0	1
h	0	0	1	0	1	2	0	2	1	0	1	1	0	2	0	0	2	0	1	17	5
ḷ	3	2	0	2	0	1	1	2	1	1	2	3	1	2	3	5	0	2	2	3	19

Note. x-axis indicates stimulus; y-axis indicates responses.

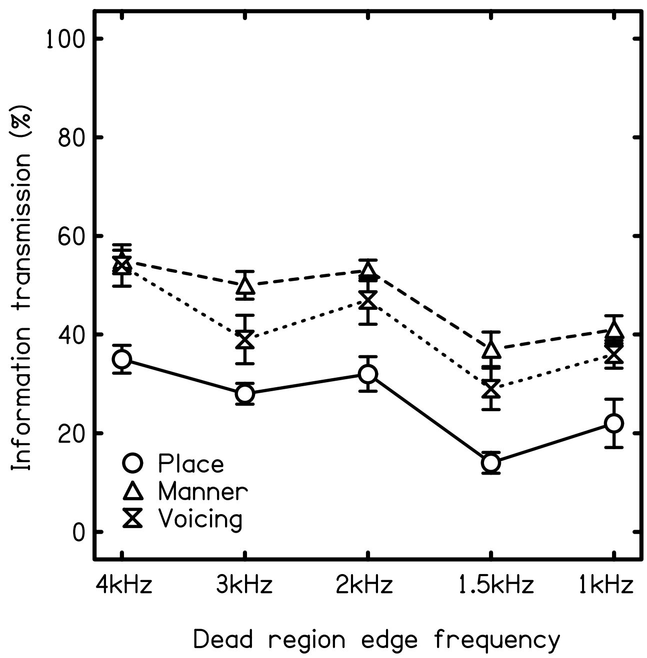

Figure R.3.7. Information transmitted in terms of place, manner and voicing features in amplification up to the *fe* condition in individuals with dead regions

The identification of bilabials, dentals and palatals was maximum in individuals having *fe* at 4000 Hz. The information transmission for place features of labiodentals, retroflex, velars and glottal was higher in individuals with *fe* of 2000 Hz and higher (Figure R.3.8). The identification scores for plosives were better for individuals having *fe* at 2000, 3000 and 4000 Hz (Figure R.3.9). However, poor scores were observed for individuals having *fe* at 1000 and 1500 Hz. The information transmission for nasals, laterals and semivowels was almost similar across all individuals. The information transmission for taps, fricatives and affricates were poorer for individuals having *fe* below 2000 Hz compared to individuals having *fe* at 2000 Hz and above. There was drastic improvement in the identification scores for affricates and fricatives for individuals having *fe* at 2000 Hz and above when amplification was provided up to the *fe* of the dead region.

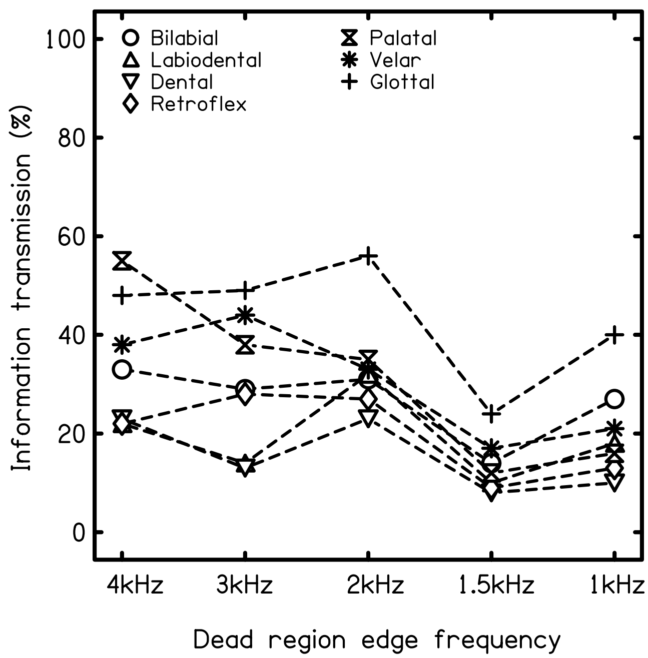

Figure R.3.8. Information transmitted for different place features in amplification up to *fe* condition in individuals with dead regions

Previous studies concluded that for amplification provided with various lowpass cut-off frequencies, the information transmitted for voicing features was maximum followed by manner and place features (Baer et al., 2002; Vickers et al., 2001). The differences in the results observed in the present study may be probably due to the differences in the linguistic and phonetic structure between two languages. The information transmission for place features was lesser since the information available for individuals with dead region decreases as the *fe* reduces.

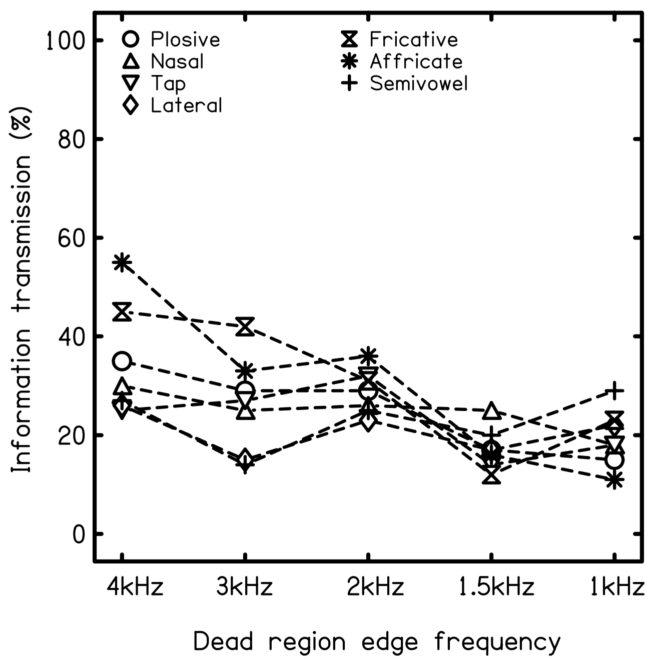

Figure R.3.9. Information transmitted for different manner features in amplification up to *fe* condition in individuals with dead regions

Studies have shown that a majority of the acoustic cues for speech identification lie in the higher frequencies and the individuals benefited from amplification of the higher frequencies (Hogan & Turner, 1998). However, the scores were lesser in individuals having *fe* below 2000 Hz as they would get limited information. These findings support the study by Moore (2001) who reported that the amount of information obtained from individuals having a higher *fe* is more than those individuals having a lower *fe* (Moore, 2001). The identification of bilabials was lesser in individuals having *fe* at 1000 and 1500 Hz may be because plosives have dominant frequency information in the low and mid frequencies (Wang et al., 1978). The identification of nasals requires broad frequency information and the scores were reduced for individuals having *fe* below 2000 Hz when amplification was provided up to *fe* when compared to the other two amplification conditions. It may be speculated that individuals with dead regions having a *fe* at 1000 Hz or 1500 Hz and extending upwards may have difficulty in the identification of fricatives and affricates which has dominant frequency information in the higher frequencies. This may be because the frequency information for taps, fricatives and affricates lies mainly in the mid to high frequencies. Hence individuals with a lower *fe* at 1000 and 1500 Hz could not obtain much information regarding these features.

3.2.4. Comparison of different amplification conditions

Comparing the three different amplification conditions in individuals with dead regions, the present study showed that the identification of manner features were comparatively better when amplification was provided up to one octave above the *fe* compared to other amplification and unaided condition. The results of the present study also indicated that consonant feature identification was least when amplification was provided up to the *fe* of the dead region. In the present study information transmitted for place features was least when amplification was provided only up to the *fe* of the dead region, especially for individuals having a lower *fe* at 1000 or 1500 Hz. The improvement in identification of place of articulation was maximum when amplification was provided up to one octave above the *fe* for individuals having *fe* below 2000 Hz. However, individuals having a higher *fe* at 2000, 3000 and 4000 Hz performed better and the scores were almost similar in the fullband and amplification up to one octave above *fe* condition. The improvement for identification of manner features was relatively lesser when amplification was provided up to the *fe* when compared to amplification up to one octave above the *fe*. Though the information transmission for voicing features was relatively lesser in the unaided condition when compared to the amplification conditions, it almost remained the same in all the three amplification conditions. It was observed that voicing features were perceived better in the amplification condition compared to the unaided condition. This may be because of duration cues available for perception of voicing. It has been reported that voiced consonants are longer than unvoiced consonants (Titze, 1994). Acoustic analyses of CVs used for the present study also showed that the duration of the voiced consonants were longer than the unvoiced consonants.

Previous studies have also shown that, for individuals with dead regions, scores for manner and place tended to improve initially with increasing cutoff frequency, but did not improve or the scores even deteriorated once the cutoff frequency was more than 50% to 100% above the estimated *fe* of the dead region (Vickers et al. 2001). The reason for individuals with dead regions obtaining limited benefit from amplification may be due to the audibility at those frequencies. Studies have shown that individuals with hearing impairment may not benefit from amplification of high frequency information (above 3000 Hz) than amplification of low frequency information, particularly when the hearing thresholds exceed 55-80 dB HL (Amos, 2001; Ching et al., 1998; Hogan & Turner, 1998; Turner & Cummings, 1999). Hogan and Turner (1998) concluded that the benefit of providing additional high-frequency audibility was negligible or negative when the degree of hearing loss at and above 4000 Hz exceeded 55 dB HL. Hence, they concluded that the total removal of high-frequency amplification should be limited to people whose high-frequency thresholds exceed 80 dB HL. In other words, selective amplification may be beneficial in individuals having dead regions (Vickers et al., 2001; Vinay & Moore, 2007b). Souza and Bishop (2000) indicated that the listeners with flat loss showed a greater rate of improvement in speech identification abilities as audibility increases than listeners with sloping loss. It may be noted that individuals with high frequency dead regions are usually associated with steeply sloping audiograms and hence the speech identification abilities in individuals with dead regions were poor even when audibility was provided. There are several reasons for the variability in the speech identification abilities observed in individuals having different *fe*. The first reason may be because of lack of audibility from different amplification conditions at certain frequencies where there is a presence of dead regions (Moore, 2001). It may be observed that as the *fe* reduces, the amount of frequency information obtained also reduces. For people with a higher *fe*, there may be sufficient speech information obtained from amplification when compared to those with lower *fe*. The second reason that individuals with dead regions may have difficulty in identifying speech sounds may be because they have to listen at high sound-pressure levels that create distortion of speech sounds. This may happen especially for individuals having a lower *fe* and in such individuals providing fullband amplification may not be beneficial (Vickers et al., 2001).

In general it was observed that individuals with dead regions having different *fe* obtained maximum benefit in terms of the place and manner features when amplification was provided up to one octave above the *fe* of the dead region. The results observed in the present study may also be related to the vowel context present with the consonant, thereby formant transition may have had an effect on the consonant identification. The information transmission for consonant identification also depends upon the *fe* and the amplification condition. It was observed that individuals having a higher *fe* obtained higher information transmission for consonant features when compared to individuals having a lower *fe*. However, voicing features were almost similar in all three amplification conditions.

Thus, from the results of the present study it is evident that audiometric slope may not be a reliable predictor of the presence or absence of a dead region. Audiometric threshold criteria may be taken as a preliminary indicator for the presence or absence of dead regions at frequencies of 3000 Hz and below. The results also indicate that, when the degree of hearing loss is matched, presence of dead region does not have a significant effect on the speech identification abilities in adults or geriatrics. But the speech identification scores showed a decreasing trend with decrease in *fe*. Thus, speech identification abilities in individuals with dead regions depend upon the extent of the dead region and the amplification condition.

CHAPTER V

SUMMARY AND CONCLUSIONS

A dead region in the cochlea has been defined as ‘a region in the cochlea where inner hair cells and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening (Moore, 2004). The diagnosis of dead regions in individuals with hearing-impairment may be important, as their presence may influence the rehabilitation strategy. Usually, the initial fitting of hearing aids is based on the audiogram, which does not reliably identify or delimit dead regions (Moore, 2001). It is likely that high-frequency amplification may play a limited role in improving, and may even impair speech identification in individuals with high-frequency dead regions (Ching, Dillon & Byrne, 1998; Markessis et al., 2004; Murray & Byrne, 1986; Rankovic, 1991; Van Tasell & Turner, 1984).

The present study investigated whether audiometric slope and/or threshold can predict the presence or absence of dead regions in participants with sensorineural hearing loss. It was also aimed to investigate and compare the speech identification abilities in participants with and without dead regions. Further, the present study investigated the benefits of selective amplification in participants with dead regions and the identification of different features of consonants in different amplification conditions.

Data were collected from 208 participants (372 ears; 74 females and 134 males) with sensorineural hearing impairment. The TEN (HL) test was administered to identify the presence or absence of dead regions in participants with sensorineural hearing impairment. Participants with dead regions were further classified based on the edge frequency of the dead region. The groups included those having edge frequency of 1000, 1500, 2000, 3000 and 4000 Hz. The audiometric threshold and slope values were estimated in these participants. The speech identification abilities were assessed for both the groups of participants using bisyllabic word list in Kannada. Benefit from amplification was investigated by assessing speech identification scores for CV list with and without a hearing aid. Speech material was amplified through a digital hearing aid according to the NAL-NL1 formula (Dillon, 1999). For participants with dead regions, speech identification abilities were assessed in three different amplification conditions- fullband, amplification up to one octave above *fe* and amplification up to the *fe*. For participants without dead regions, speech identification abilities were assessed in fullband condition.

The data thus obtained were subjected to appropriate statistical analyses, which included t-test for Independent Samples, Paired t-test, nonparametric Chi-square test and Analyses of Variance (ANOVA). To check the efficiency of audiometric slope in predicting the presence or absence of a dead region, the hit rate, miss rate, false alarm and correct rejection rates were calculated by comparing the prediction made based on the audiometric criteria with the results of TEN test.

To investigate the identification of consonants, the percentage of input information transmitted for a given feature was determined using SINFA Analyses Suite "FIX" software (Mike Johnson, Department of Phonetics & Linguistics, University College London; www.phon.ucl.ac.uk.resource.htm). The consonant features were categorized based upon the classification system given by Ramaswami (1999). The consonants were analyzed to determine the percentage information transmission for the phonetic features of place, manner and voicing (Miller & Nicely, 1955). Some of the important results revealed by the analyses are as follows:

a. Comparison of slope of the audiogram with the presence or absence of dead regions at different frequencies

- Slope per octave and slope per mid octave values for ears with dead regions are significantly higher when compared to ears without dead regions. However, there is an overlap of slope values of both the groups of participants.

b. Predicting the presence or absence of dead regions based on audiogram in participants with sensorineural hearing loss

- Audiometric threshold criteria are better than the slope criteria or the combined criteria of slope and threshold, in predicting dead regions.
- Audiometric threshold criteria may be taken as a preliminary indicator for the presence or absence of a dead region at frequencies of 3000 Hz and below since it leads to both high hit rate and correct rejection rate.

c. Investigation and comparison of speech identification scores in participants with or without dead regions

- Presence of dead region did not have a significant effect on the speech identification abilities when the degree of hearing loss is matched, but there is a trend of decreasing speech identification ability with increase in *fe* of the dead region.

- The results showed that the information transmission for place features was better in participants without dead regions when compared to those with dead regions.
- The information transmission for manner features is similar in participants without dead regions and participants with dead regions having *fe* at 3000 and 4000 Hz but are higher when compared to participants having dead regions having *fe* of 2000 Hz, 1500 Hz or 1000 Hz.
- Identification of the voicing features almost remained similar in participants with and without dead regions.

d. Speech identification scores in different amplification conditions in participants with dead regions

- Participants without dead regions obtained more benefit when compared to participants with dead regions in fullband amplification condition.
- The mean speech identification scores was significantly higher when amplification was provided up to one octave above the *fe* compared to the unaided, fullband and amplification up to the *fe* condition, for participants having *fe* at 1000, 1500 or 2000 Hz.
- Providing fullband amplification resulted in better speech identification scores compared to the unaided and amplification up to the *fe* conditions. The place features were perceived the least followed by voicing and manner.

- Providing amplification up to one octave above the *fe* resulted in better identification of consonants when compared to unaided and other two amplification conditions.
- Providing amplification up to the *fe*, the information transmission for place features was least for all the participants when compared to the other two amplification conditions.
- Information transmission for place features was higher in the amplification up to one octave above the *fe* condition when compared to the unaided and other two amplification conditions. Information transmission for manner features was highest in the amplification up to one octave above the *fe* condition when compared to the unaided condition and other two amplification conditions.
- Information transmission for voicing features improved with amplification compared to unaided condition but remained similar in all the three amplification conditions.

Implications of the study

Thus, from the results of the present study it is evident that diagnosis of dead regions is required while selecting a hearing aid for individuals with high-frequency hearing loss. Speech identification abilities in participants with dead regions depend upon the extent of the dead region and the amplification condition. For participants without a dead region, fullband amplification may be provided. For participants with high frequency dead regions having *fe* at 2000 Hz and below, it is advantageous to provide amplification up to one octave above the estimated *fe* of the dead region.

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 the American Academy of Audiology, 18*, 97-106.

Amos, N. E., & Humes, L. E. (2001). The contribution of high frequencies to speech recognition in sensorineural hearing loss, in *Physiological and Psychophysical Bases of Auditory Function*, edited by D. J. Breebaart, A. J. M. Houtsma, A. Kohlrausch, V. F. Prijs and R. Schoonhoven (Shaker, Maastricht).

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.

ANSI (1969). *ANSI S3.5–1969*, *Methods for the calculation of the articulation index,* (American National Standards Institute, New York).

ANSI (1987). *ANSI S3.39-1987 (R2007), Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance),* American National Standard Institute, New York).

ANSI (1997). *ANSI S3.5-1997. Methods for calculation of the speech Intelligibility Index,* (American National Standards Institute, New York).

ANSI (1999). *Maximum permissible ambient noise levels for audiometric test rooms.* New York, American National Standards Institute.

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

Beattie, R. C. (1982). Comfortable speech listening levels: Effects of competition and instructions. *The American Journal of Otology, 3,* 192-199.

Beattie, R. C., & Warren, V. (1983). Slope characteristics of CID W-22 word functions in elderly hearing-impaired listeners. *Journal of Speech and Hearing Disorders, 48,* 119-127.

Beattie, R. C., & Zipp, J. A. (1990). Range of intensities yielding PB max and the threshold for monosyllabic words for hearing-impaired subjects. *Journal of Speech and Hearing Disorders, 55,* 417- 426.

Bess, F. H., & Townsend, T. H. (1977). Word discrimination for listeners with fiat sensorineural hearing losses. *Journal of Speech and Hearing Disorders,42,* 232-237.

Bilger, R.C., & Wang, M.D. (1976). Consonant confusions in patients with sensorineural hearing loss. *Journal of Speech Hearing Research, 19(4)*, 718-748.

Boothroyd, A. (1978). *Speech Perception and Sensorineural Hearing Loss.* In M. Ross & G. Giolas (Eds.), Auditory Management of the Hearing-Impaired Child. Baltimore: University Park Press.

Borden, G.J., & Harris, K.S. (2007). *Speech Science Primer: Physiology, Acoustics and Perception of Speech*, Baltimore: Williams and Wilkins.

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

Carlyon, R.P. & Moore, B.C.J. (1984). Intensity discrimination: A severe departure from Weber's law, *Journal of the Acoustical Society of America, 76,* 1369-1376.

Carney, A. & Moeller, M. (1998). Treatment efficacy: Hearing loss in children. *Journal of Speech, Language, and Hearing Research, 41,* S61-S84.

CHABA (Committee on Hearing, Bioacoustics and Biomechanics) (1988). Speech understanding and aging. *Journal of the Acoustical Society of America, 83(3),* 859-895.

Cheesman, M.F., Hepburn, D., Armitage, J.C., & Marshall, K. (1995). Comparison of growth of masking functions and speech discrimination abilities in younger and older adults, *Audiology, 34,* 321-333.

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

Chistovich, L.A. (1957). Frequency characteristics of masking effect. *Biophysics, 2,* 743-755.

Clark, J. G., (1981). Uses and abuses of hearing loss classification. *American Speech-Language-Hearing Association*, 23, 493-500.

Corso, J.F. (1971). Sensory processes and age effects in normal adults. *Journal of Gerontology, 26,* 90-105.

Cox, R., Alexander, G., & Gilmore, C. (1987). Development of the Connected Speech Test (CST). *Ear and Hearing*, *8*, 119–126.

Cox, R., Alexander, G., Gilmore, C., & Pusakulich, K. (1988). Use of the Connected Speech Test (CST) with hearing-impaired listeners. *Ear and Hearing*, *9*, 198–207.

Crandell, C.C. (1993). Speech recognition in noise by minimal degrees of sensorineural hearing loss, *Ear and Hearing, 14 (3),* 210-216.

Davis, J., Elfenbein, J., Schum, R., & Bentler, R. (1986). Effects of mild and moderate hearing impairments on language, educational, and psychosocial behavior of children. *Journal of Speech and Hearing Disorders, 51*, 53–62.

Dillon, H. (1999). NAL-NL1: A new prescriptive fitting procedure for non-linear hearing aids. *Hearing Journal, 52(4),* 10-16.

Dreschler, W. A. (1980). Reduce d speech intelligibility and its psychophysical correlates in hearing-impaired listeners. In G. van den Brink & F. A. Bilsen (Eds.), *Psychophysical, physiological and behavioral studies in hearing* (pp. 466-471). The Netherlands: Delft University Press.

Dreschler, W.A., & Plomp, R. (1980). Relation between psychophysical data and speech perception in hearing-impaired subjects. I. *Journal of the Acoustical Society of America, 68(6),* 1608-1615.

Dubno, J.R., & Ahlstrom, J.B. (1995). Masked thresholds and consonant recognition in low-pass maskers for hearing-impaired and normal-hearing listeners. *Journal of the Acoustical Society of America, 97(4),* 2430-2441.

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 the Acoustical Society of America, 85(1),* 347-354.

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., & Morgan, D.E. (1982). Effects of mild hearing loss and age on speech recognition in noise, *Journal of the Acoustical Society of America, 72(1),* S34-S35.

Dubno, J.R., Dirks, D.D. & Morgan, D.E. (1984). Effects of age and mild hearing loss on speech recognition in noise, *Journal of the Acoustical Society of America, 76(1),* 87-96.

Dubno, J.R., Dirks, D.D. & Schaefer, A.B. (1987). Effects of hearing loss on utilization of short-duration spectral cues in stop consonant recognition, *Journal of the Acoustical Society of America, 81(6),* 1940-1947.

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 the Acoustical Society of America, 85(1),* 355-64.

Dubno, J.R., Horwitz, A.R., & Ahlstrom, J.B. (2003). Recovery from prior stimulation: Masking of speech by interrupted noise for younger and older adults with normal hearing, *Journal of the Acoustical Society of America, 113(4),* 2084-2094.

Elfenbein, J. L., Hardin-Jones, M. A., & Davis, J. M. (1994). Oral communication skills of children who are hard of hearing. *Journal of Speech and Hearing Research, 37,* 216–226.

Egan, J. P., & Hake, H. W. (1950). On the masking pattern of a simple auditory stimulus, *Journal of the Acoustical Society of America, 22,* 622-630.

Festen, J.M., & Plomp, R. (1983). Relations between auditory functions in impaired hearing. *Journal of the Acoustical Society of America, 73(2),* 652-662.

Findlay, R. C., & Denenberg, L.J. (1977). Effects of subtle mid-frequency auditory dysfunction upon speech discrimination in noise. *Audiology, 16,* 252-259.

Fitzgibbons, P.J., & Gordon-Salant, S. (1994). Age effects of measures of auditory duration discrimination. *Journal of Speech & Hearing Research, 37,* 662-670.

Fletcher, H. (1953). *Speech and Hearing in Communication*, New-York: Krieger.

Florentine, M. (1983). Intensity discrimination as a function of level and frequency and its relation to high-frequency hearing. *Journal of the Acoustical Society of America, 74(5),* 1375-1379.

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

Fougeron, C. & P. Keating. 1997. Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustic Society of America 101,* 3728-3740.

Franklin, B. (1975). A comparison of the effect on consonant discrimination of combining low- and high-frequency passbands on consonant recognition in the hearing impaired. *Journal of Speech & Hearing Research, 18,* 719–727.

French, N. R., & Steinberg, J. C. (1947). Factors governing the intelligibility of speech sounds. *Journal of the Acoustical Society of America, 19,* 90-119.

Garrett, H.E., & Woodworth, R.S. (1966). *Statistics in psychology and education.* Mumbai: Vakils, Feffer and Simon Limited.

Geetha, C., Ashly, G., & Yathiraj, A. (2005). *Perception of high frequency filtered speech in normal hearing subjects.* Unpublished paper presented at the 37th Indian Speech & Hearing Association held at Indore, India.

Glasberg, B.R., & Moore, B.C.J. (1990). Derivation of auditory filter shapes from notched-noise data. *Hearing Research, 47,* 103-38.

Gordon-Salant, S. (1984). Effects of reducing low-frequency amplification on consonant perception in quiet and noise. *Journal of Speech and Hearing Research, 27,* 483-493.

Gordon-Salant, S. (1987). Consonant recognition and confusion patterns among elderly hearing-impaired subjects. *Ear and Hearing, 8(5),* 270-276.

Gravendeel, D.W., & Plomp, R. (1960). Perceptive bass deafness. *Acta Otolaryngologica, 51,* 549–560.

Gutnick, H.N. (1982). Consonant-feature transmission as a function of presentation level in hearing-impaired listeners. *Journal of the Acoustical Society of America,72(4),* 1124-1130.

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.

Hedrick, M. (1997). Effect of acoustic cues on labeling fricatives and affricates. *Journal of Speech, Language, and Hearing Research*, *40,* 925-938.

Hedrick, M., & Carney, A. E. (1997). Effect of relative amplitude and formant transitions on perception of place of articulation by adult listeners with cochlear Implants. *Journal of Speech, Language, and Hearing Research*, *40,* 1445-1457.

Hedrick, M., & Jesteadt, W. (1996). Effect of relative amplitude, presentation level, and vowel duration on perception of voiceless stop consonants by normal and hearing-impaired listeners. *Journal of the Acoustical Society of America*, *100,* 3398-3407.

Hedrick, M., & Younger, M. S. (2001). Perceptual weighting of relative amplitude and formant transition cues in aided CV syllables. *Journal of Speech, Language, and Hearing Research*, *44,* 964-974.

Hedrick, M., & Younger, M.S. (2007). Perceptual weighting of stop consonant cues by normal and impaired listeners in reverberation versus noise. *Journal of Speech, Language and Hearing Research, 46(3),* 636-648.

Hicks, C.B, & Tharpe, A.M. (2002). Listening Effort and Fatigue in School Age Children With and Without Hearing Loss. *Journal of Speech, Language & Hearing Research, 45,* 573-584.

Hogan, C.A., & Turner, C.W. (1998). High frequency audibility: Benefits for hearing-impaired listeners. *Journal of the Acoustical Society of America, 104,* 432-441.

Hornsby, B.W.Y., & Ricketts, T.A. (2003). The effects of hearing loss on the contribution of high- and low-frequency speech information to speech understanding. *Journal of the Acoustical Society of America,113(3),* 1706-1717.

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.

Humes, L.E., & Christopherson, L. (1991). Speech identification difficulties of hearing-imapired elderly persons: The contributions of auditory processing deficits. *Journal of Speech and Hearing Research, 33,* 726-735.

Humes, L., Dirks, D.D., Bell, T.S., & Kincaid, G.E. (1987). Recognition of Nonsense Syllables by Hearing-impaired Listeners and by Noise-masked Normal Hearers. *Journal of Acoustical Society of America, 81(3),* 765-773.

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(6),* 3283-3294.

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

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

ISO 389-8: (2004). Acoustics- Reference zero for the calibration of audiometric equipment - Part 8: Reference equivalent threshold sound pressure levels for pure tones and circumaural earphones. Geneva: International Organization for Standardization.

Jesteadt, W., Bacon, S. P., & Lehman, J.R. (1982). Forward masking as a function of frequency, masker level, and signal delay. *Journal of the Acoustical Society of America, 71(4),* 950-962.

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.

Kamm, C.A., Dirks, D.D., & Bell, T.S. (1985). Speech recognition and the articulation index for normal and hearing-impaired listeners. *Journal of the Acoustical Society of America, 77(1),* 281-288.

Kapadia, S., Blakemore, S., Graumann, D., & Phillips, A. (2002). Prevalence of cochlear dead regions in patients with high-frequency sensorineural hearing loss, Poster presented at the International Hearing Aid Conference, Lake Tahoe, CA, August 2002.

Kent, D.R., & Read, C. (1995). *The Acoustic analysis of speech,* Delhi: A.I.T.B.S. Publishers.

Kiang, N.Y.S & Moxon, E.C. (1974). Tails of tuning curves of auditory-nerve fibers. *Journal of the Acoustical Society of America, 55(3),* 620-630.

Kiessling, J., Brenner, B., Ostergaard Olsen, S. & Dyrlund, O. (2001). Identification of dead cochlear regions-valuable information for hearing aid fitting? Fifth European Federation of Audiology Societies, Bordeaux.

Killion, M. (1997). The SIN report: Circuits haven't solved the hearing-in-noise problem. *The Hearing Journal, 50(10),* 28-32.

Klatt, D.H. (1987). Acoustic correlates of breathiness: First harmonic amplitude, turbulence noise and tracheal opening. *Journal of the Acoustical Society of America, 82 (Suppl 1),* S91.

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

Ladefoged, P., & Maddieson, I. (1996). *Sounds of the world's languages*. Oxford: Blackwell Publishers.

Langenbeck, B. (1965). *Textbook of Practical Audiometry,* New York: Edward Arnold.

Liberman, M. C., & Dodds, L. W. (1984). Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations to threshold tuning curves. *Hearing Research, 16,* 55–74.

Liberman, M.C., Dodds, L.W., & Learson, D.A. (1986). Structure-function correlation in noise-damaged ears: a light and electron-microscopic study. In R.J.Salvi, D. Henderson, R.P.Hamernik, & V.Colletti (eds) Basic and applied aspects of noise-induced hearing loss. New York: Plenum Press.

Liberman, M.C, Dodds, L.W, & Pierce, S. **(**1990**).** Afferent and efferent innervation of the cat cochlea: quantitative analysis with light and electron microscopy. *Journal of Computational Neurology, 301,* 443-460.

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 the American Academy of Audiology, 15,* 498-507.

Markessis, E., Kapadia, S., Munro, K. J., & Moore, B. C. J. (2006). Modification of the TEN test for cochlear dead regions for use with steeply sloping high-frequency hearing loss. *International Journal of Audiology*, *45(2)*, 91-98.

Miller, G. A., & Nicely, P. E. (1955). An analysis of perceptual confusions among some English consonants, *Journal of the Acoustical Society of America, 27,* 338-352.

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

Moore, B. C. J. (1995). *Perceptual Consequences of Cochlear Damage.* Oxford, Oxford University Press.

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

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. (2002). Practical application of the TEN test for diagnosis of dead regions. *Iranian Audiology, 1,* 17-21.

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

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

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

Moore, B. C. J., & Glasberg, B. R. (1998). Use of a loudness model for hearing aid fitting. I. Linear hearing aids, *British Journal of Audiology, 32*, 317-335.

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(5),* 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 Audiology, 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.

Munro, K.J., Felthouse, C., Moore, B.C.J., & Kapadia, S. (2005). Reassessment of cochlear dead regions in hearing-impaired teenagers with severe-to-profound hearing loss. *International Journal of Audiology*, *44*, 470-477.

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.

Nabalek., A.K, & Donahue., A.M. (1984). "Perception of consonants in reverberation by native and non-native listeners, *Journal of the Acoustical Society of America* 79, 2078-2082.

Norbury, C.F., Bishop, D.V.M., & Briscoe, J. (2001). Production of English finite verb morphology: A comparison of mild-moderate hearing impairment and specific language impairment. *Journal of Speech, Language and Hearing Research, 44,* 165-178.

Ohde, R.N., & Stevens, K.N. (1983). Effect of burst amplitude on the perception of stop consonant place of articulation. *Journal of the Acoustical Society of America, 74,* 706-714.

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

Patterson, R.D., & Nimmo-Smith, I. (1980). Off-frequency listening and auditory filter asymmetry. *Journal of the Acoustical Society of America, 67,* 229-245.

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.

Pavlovic, C.V. (1984). Use of the articulation index for assessing residual auditory function in listeners with sensorineural hearing impairment" *Journal of the Acoustical Society of America, 75,* 1253-1258.

Pavlovic C. V. (1987). Derivation of primary parameters and procedures for use in speech intelligibility predictions. *Journal of the Acoustical Society of America, 82,* 413-422.

Pavlovic, C.V., Studebaker, G.A., & Sherbecoe, R.L. (1986). An Articulation Index Based Procedure for Predicting the Speech Recognition Performance of Hearing-impaired Individuals, *Journal of the Acoustical Society of America, 80,* 50-57.

Phillips, S.L., Gordon-Salant, S., Fitzgibbons, P.J., & Yeni-Komshian, G. (2000). Frequency and temporal resolution in elderly listeners with good and poor word recognition. *Journal of Speech, Language and Hearing Research, 43(1),* 217-228.

Pisoni, D.B., & Remez, R.E. (2005). The handbook of speech perception. Oxford: Blackwell Publishers.

Plomp, R. (1978). Auditory Handicap of hearing impairment and the limited benefit of hearing aids. *Journal of the Acoustical Society of America, 63,*533-549.

Plomp, R., & Mimpen, A.M. (1979). Speech-reception threshold for sentences as a function of age and noise level. *Journal of the Acoustical Society of America, 66,* 1333-1342.

Posner, J., & Ventry, I.M. (1977). Relationships between comfortable loudness levels for speech and speech discrimination in sensorineural hearing loss. *Journal of speech and Hearing Disorders, 42(3),* 370-5.

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 the American Academy of Audiology*, *16*, 600-613.

Preminger, J. E., & Wiley, T.L. (1985). Frequency selectivity and consonant intelligibility in sensorineural hearing loss. *Journal of speech and Hearing Research, 28(2),* 197-206.

Quaranta A., Sallustio V., & Quaranta N. (2001) Noise induced hearing loss: Summary and perspectives. In Noise induced hearing loss: Basic mechanisms, prevention and control. Henderson D., Prasher D., Kopke R., Salvi R., Hamernik R., eds. Noise Research Network Publications, London, pp 539-557.

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

Rankovic, C. M. (1991). An application of the articulation index to hearing aid fitting. *Journal of Speech and Hearing Research, 34,* 391-402.

Reed, C. (1975). Identification and discrimination of vowel-consonant syllables in listeners with sensorineural hearing loss. *Journal of Speech and Hearing Research, 18(4),* 773-794.

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

Revoile, S., Pickett, J., and Kozma-Spytek, L. (1991). Spectral cues to perception of /d,n,l/ by normal-and impaired-hearing listeners. *Journal of the Acoustical Society of America, 90 (2),* 787-798.

Ricketts, T.A, & Tharpe, A.M. (2005). Directional Microphone Technology for Children. In: Seewald, RC & Bamford J (Eds.), *A Sound Foundation Through Early Amplification,* Proceedings of the Third International Conference.

Ruggero, M.A., Rich, N.C., Recio, A., Narayan, S.S., & Robles, L. (1997). Basilar membrane responses to tones at the base of the chinchilla cochlea. *Journal of the Acoustical Society of America, 101,* 2151-63.

Sachs, M. B. & Young, E.D. (1980). Effects of nonlinearities on speech encoding in the auditory nerve. *Journal of the Acoustical Society of America, 68,* 858-875.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403-428.

Sammeth, C.A., Tetzeli, M., & Ochs, M.T. (1996). Consonant recognition performance of hearing-impaired listeners using one linear and three nonlinear hearing aids. *Journal of American Academy of Audiology, 7(4),* 240-250.

Savithri, S.R. (1989). Acoustical and psychological correlates of speech. *Journal of Acoustical Society of India, 17(3,4),* 41-48.

Savithri, S.R. (1996). Speech perception: Development of speech perception in Kannada speaking children (personal communication).

Schmiedt, R.A, Mills, J.H, & Boettcher, F.A. (1996). Age-related loss of activity of auditory-nerve fibers. *Journal of Neurophysiology, 76,* 2799-2803.

Schneider, B. (1997). Psychoacoustics and aging: Implications for everyday listening. *Journal of speech-Language Pathology and Audiology, 21,* 111-124.

Schuchman, G., Valente, M., Beck, L. & Potts, L. (1999). User satisfaction with an ITE directional hearing instrument. *The Hearing Review*, *6*: 12, 16, 21, 22.

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, 44,* 408-420.

Shannon, R.V., Zeng, F.G., & Wygonski, J. (1998). Speech recognition with altered spectral distribution of envelope cues. *Journal of the Acoustical Society of America,104(4),* 2467-2476.

Silman, S., & Silverman, C.A. (1991). *Auditory Diagnosis; Principles and Applications.* San Deigo: Academic Press.

Silva, C., & Feitosa, G. (2006). High-frequency audiometry in young and older adults when conventional audiometry is normal, *Revista Brasileira De Otorrinolaringologia, 72(5),* 665-672.

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-induced hearing loss: Effects of high frequency compensation. *Journal of the Acoustical Society of America,67(1),* 306-317.

Smith-Olinde, L., Besing, J., & Koehnke, J. (2004). Interference and enhancement effects on interaural time discrimination and level discrimination in listeners with normal hearing and those with hearing loss. *American Journal of Audiology, 13(1),* 80-95.

Sommers, M.S., & Danielson, S.M. (1999). Inhibitory processes and spoken word recognition in young and older adults: The interaction of lexical competition and semantic context. *Psychology and Aging, 14,* 458-472.

Souza, P.E., & Bishop, R.D. (2000). Improving audibility with nonlinear amplification for listeners with high frequency loss, *Journal of the American Academy of Audiology*, *11,* 214-223.

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

Stelmachowicz, P.G., Beauchaine, K.A., Kalberer, A., & Jesteadt, W. (1989). Normative thresholds in the 8-to-20 kHz range as a function of age, *Journal of the Acoustical Society of America, 86(4),* 1384-1391.

Stevens, K. (1985). Evidence for the role of acoustic boundaries in the perception of speech sounds. In V.A. Fromkin (ed.) *Phonetic linguistics: Essays in honor of Peter Ladefoged,* (pp.243-255), London: Academic Press.

Strickland, E.A., Viemeister, N.F., Van Tasell, D.J., & Preminger, J.E. (1994). Is useful speech information carried by fibers high characteristic frequencies? *Journal of Acoustic Society of America, 95,* 497-501.

Studebaker, G.A., Sherbecoe, R.L., McDaniel, D.M., & Gray, G.A. (1997). Age-related changes in monosyllabic word recognition performance when audibility is held constant. *Journal of the American Academy of Audiology 8,* 150-162.

Thai-Van, H., Micheyl, C., Norena, A., & Collet, L. (2002). Local improvement in auditory frequency discrimination is associated with hearing-loss slope in subjects with cochlear damage. *Brain, 125(3),* 524-537.

Titze, I.R. (1994). *Principles of voice production.* New York: Prentice Hall, Englewood Cliffs.

Tobias, J. V. (1977). The need for preventive Audiology, *Audiology and Hearing Education, 3(2),* 37-38.

Townsend, T.H., & Bess, F.H. (1980). Effects of age and sensorineural hearing loss on word recognition. *Scandinavian Audiology, 9,* 245-248.

Tsui, I. Y. H., & Ciocca, V. (2000). The perception of aspiration and place of articulation of Cantonese initial stops by normal and sensorineural hearing-impaired listeners.

The International Journal of Language and Communication Disorders, *35,* 507-525.

Turek, S., Dorman, M., Franks, J., & Summerfield, Q. (1980). Identification of synthetic /bdg/ by hearing impaired listeners under monotic and dichotic formant presentation, *Journal of the Acoustical Society of America, 67,* 1031-1040.

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

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., & Henry, B.A. (2002). Benefits of amplification for speech recognition in background noise. *Journal of the Acoustical Society of America*, *112(4),* 1675-1680.

Turner, C.W., & Robb, M. (1987). Audibility and Recognition of Stop Consonants in Normal and Hearing-Impaired Adults. *Journal of the Acoustical Society of America*, *81,* 1566-1573.

Turner, C.W., Souza, P.E., & Forget, L.N. (1995). Use of temporal envelope cues in speech recognition by normal and hearing-impaired listeners. *Journal of Acoustical Society of America*, *97,* 2568-2576.

Tyler, R.S., & Summerfield, A.Q. (1980). Psychoacoustical and phonetic measures of temporal processing in normal and hearing-impaired listeners. In G. van den Brink and F.A. Bilsen (Eds.) *Psychophysical, Physiological, and Behavioural Studies in Hearing.* (pp. 458-465), Delft University Press, Delft, Nederlands.

Van Son, R.J.J.H. & Pols, L.C.W. (1990). Formant frequencies of Dutch vowels in a text, read at normal and fast rate. *Journal of the Acoustical Society of America, 75,* 1683-1693.

Van Son, R.J.J.H. & Pols, L.C.W. (1996). An acoustic profile of consonant reduction, Proceedings of ICSLP 96, Philadelphia, USA, 1529-1532.

Vandana, S. (1998). Speech identification test for Kannada speaking children. Unpublished independent project, University of Mysore, Mysore, Karnataka.

Van Tasell, D. J. (1993). Hearing loss, speech, and hearing aids. *Journal of Speech and Hearing Research, 36(2),* 228–244.

van Tasell, D. J., & Turner, C. W. (1984). Speech recognition in a special case of low-frequency hearing loss, *Journal of the Acoustical Society of America, 75,* 1207-12.

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

Vickers, D. A., Moore, B. C. J., & Baer, T. (2001). Effects of low pass 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.

Villchur, E. (1973). Signal processing to improve speech intelligibility in perceptive deafness. *Journal of the Acoustical Society of America, 53(6),* 1646-1657.

Vinay, & Moore, B.C.J. (2002). Effects of high pass filtering on speech intelligibility in subjects with normal hearing and subjects with and without dead regions at low frequencies. Unpublished Master of Philosophy thesis submitted at University of Cambridge, United Kingdom.

Vinay, & Moore, B. C. J. (2007a). Prevalence of dead regions in subjects with sensorineural hearing loss, *Ear and Hearing, 28(2),* 231-241.

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

Walden, B.E., & Montgomery, A.A. (1975). Dimensions of consonant perception in normal and hearing-impaired listeners. *Journal of Speech and Hearing Research, 18,* 444-455.

Wang, M. D., & Bilger, R. C. (1973). Consonant confusions in noise: A study of perceptual features, *Journal of the Acoustical Society of America, 54,* 1248-1266.

Wang, M. D., Reed, C. M., & Bilger, R. C. (1978). A comparison of the effects of filtering and sensorineural hearing loss on patients of consonant confusions. *Journal of Speech and Hearing Research, 21,* 5-36.

Wingfield, A., Aberdeen, J.S., & Stine, E.A. (1991). Wprd onset gating and linguistic context in spoken word recognition by young and elderly adults. *Journal of Gerontology, 46,* P127-P129.

Wingfield, A., Lindfield, K.C., & Goodglass, H. (2000). Effects of age and hearing sensitivity on the use of prosodic information in spoken word recognition. *Journal of Speech, Language and Hearing Research, 43,* 915-925.

Yates, G.K. (1990). Basilar membrane non-linearity and its influence on auditory nerve rate-intensity functions. *Hearing Research, 50,* 145-62.

Zurek, P., & Delhorne, L. (1987). Consonant reception in noise by listeners with mild and moderate sensorineural hearing impairment, *Journal of the Acoustical Society of America, 82,* 1548-1559.

Appendix A. Bisyllabic Word List in Kannada

1. /kannu/
2. /hu:vu/
3. /ka:ge/
4. /kappe/
5. /mola/
6. /e:ni/
7. /maḷe/
8. /lo:ṭa/
9. /da:ra/
10. /tʃa:ku/
11. /mane/
12. /nalli/
13. /o:le/
14. /bassu/
15. /kattu/
16. /gu:be/
17. /tʃatri/
18. /me:ke/
19. /se:bu/
20. /bi:ga/
21. /la:ri/
22. /mu:gu/
23. /ka:ge/
24. /giṇi/
25. /taṭṭe/
26. /sara/
27. /ka:ru/
28. /pennu/
29. /ni:ru/
30. /baḷe/
31. /a:ne/
32. /tʃendu/
33. /hallu/
34. /mara/
35. /mi:nu/
36. /na:ji/
37. /ko:ḷi/
38. /kivi/
39. /ili/
40. /su:rja/
41. /ka:su/
42. /ka:lu/
43. /ele/
44. /tʃi:la/
45. /me:dʒu/
46. /su:dʒi/
47. /ganṭe/
48. /railu/
49. /tale/
50. /ha:vu/

Appendix B. Consonant Vowel list

1. /ka/
2. /ga/
3. /tʃa/
4. /dʒa/
5. /ṭa/
6. /ḍa/
7. /ṇa/
8. /ta/
9. /da/
10. /na/
11. /pa/
12. /ba/
13. /ma/
14. /ja/
15. /ra/
16. /la/
17. /va/
18. /ʃa/
19. /sa/
20. /ha/
21. /ḷa/