Effect of Frequency Compression on Speech Identification in Noise and Localization in Individuals with Hearing Impairment

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Certificate

This is to certify that this masters dissertation entitled **Effect of Frequency Compression on Speech Identification in Noise and Localization in Individuals with Hearing Impairment** is a bonafide work in part fulfilment for the degree of Master of Science (Audiology) of the student **Registration No. 11AUD007**, this has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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This is to certify that this masters dissertation entitled **Effect of Frequency Compression on Speech Identification in Noise and Localization in Individuals with Hearing Impairment** has been prepared under my guidance and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Declaration

This masters dissertation entitled **Effect of Frequency Compression on Speech Identification in Noise and Localization in Individuals with Hearing Impairment** is the result of my own study under the guidance of Prof. P. Manjula, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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By God's Grace….

With blessings from Amma, Pappa, Anna….

Dedicated to My Guide

Prof. P. Manjula

Bowing with deep respect to our director

Prof. S. R. Savithri

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CHAPTER1

INTRODUCTION

Most individuals with sensorineural hearing impairment have a greater loss for high frequency sounds than for low frequency sounds. For some of them high frequency hearing loss is so great that they cannot extract any useful information from the high frequency sounds of speech. This occurs even if the speech is amplified sufficiently to be audible (Dillon, 2001). According to Dillon (2001) for sloping losses when high frequency thresholds are 70 dB HL or greater, the high frequency sounds of speech apparently contribute very little or no information; worse still for some of them making the high frequency parts of speech audible can decrease their ability to use information from the low- and mid- frequencies of the signal.

Literature has revealed that the most prevalent audiometric configuration among adults with hearing loss is the sloping type which is around 50% (Pittman &Stelmachowicz, 2003). Usually individuals with this type of audiogram configuration present with complaints of difficulty in understanding speech, especially in the presence of background noise. Hearing aid is the preferred form of management for such individuals.

American Speech Language Hearing Association (1998) has asserted that amplification should provide audibility and comfort for soft and average input levels, and tolerance for high input levels. The primary goal of current hearing aid fitting strategies is to make the speech signal audible in those regions where the sensitivity is reduced, and in the case of high frequency hearing loss this means providing high frequency amplification.

The bandwidth of conventional hearing aids is not broad enough to make high frequency sounds consistently audible for individuals with hearing loss (Stelmachowicz, Pittman, Lewis, & Hoover, 2003). This limits the audibility of important high frequency sounds, especially for individuals with a sloping and/or severe to profound hearing loss.

The need to provide audibility of high frequency information to listeners with greater hearing impairment is contentious (Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998; Plyler& Fleck, 2006; Turner & Henry, 2002). Larger variability in aided listening performance is thought to be due to both the level of high frequency audibility the listener is receiving as well as the ability of the listener to extract useful information from the audible signals.

There are equivocal reports in literature regarding the usefulness of high frequency amplification for individuals with sloping hearing loss. A few studies suggest that listeners who are provided with audibility at frequencies where hearing levels are severe and/or sloping will not show speech recognition benefit (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katch, & Byrne, 2001; Hogan & Turner, 1998). This is thought to be due to limited ability to use the amplified signal in the frequency region. On the other hand, other studies have reported that significant improvements in speech understanding especially in noisy environments occurs when listeners with sloping sensorineural hearing loss are provided with high frequency information (Plyler& Fleck, 2006; Turner & Henry, 2002).

To overcome the problem faced by individuals with a sloping hearing loss, frequency lowering technology is implemented in hearing devices. This shifts the high frequency components to a lower frequency range where audibility is more useful. This has been shown to improve the production and recognition of high frequency speech sounds for children and adults with severe to profound hearing loss (Auriemmo et al., 2009; Glista, Scollie, Bagatto, Seewald, Parsa, & Johnson, 2009; Kuk, Keenan, Korhonen, & Lau, 2009)

The two types of frequency lowering technology used in hearing devices include frequency transposition and frequency compression. In frequency transposition, the high frequency signal is transposed or moved down to lower frequency region where it is more able to analyse the signal. The frequency compression proportionally compresses high frequency signal into a lower frequency range by reducing the bandwidth and frequency of the signal. The latter attempts to preserve the relationship of the high frequency energy peak while leaving low frequency information uncompressed but amplified.

A few studies have been conducted to examine the use of frequency lowering technology (Miller-Hansen, Nelson, Wider, & Simon, 2003). Studies have shown that Non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses (McDermott, Dorkos, Dean, &Ching, 1999; Simpson, Hersbach, & McDermott, 2006; Hrishikesan&Manjula, 2009; Bohnert, Nyfellar, &Keilmann, 2010; Anjana&Geetha, 2011). Researchers have also reported beneficial effects of frequency transposition technique (McDermott & Knight, 2001; Raj &Rajalakshmi, 2007)

Transposing frequencies to a region one octave below the start frequency shifts the high frequency information to a lower frequency region where it may be utilized better (Moore, 2004). Additionally, temporal and spectral characteristics of the input signal below the start frequency are unaffected. In this manner, high frequency cues can be made available to the listener without introducing unnecessary distortion.

A hearing aid influences the performance of individuals in terms auditory skills such as speech audibility, speech identification, and localization. Apart from affecting the speech identification, the frequency lowering technique in hearing aids may influence localization. Localization is one of the major functions of the human ear and is a term used to describe the location of a sound source in the environment. This activity allows one to know the direction of the sound source in a three-dimensional space (Flamme, 2002)

The binaural cues have received a great deal of attention from researchers Flamme(2002). According to Fischer and Weber (2013) some aspects of auditory localization require bilateral processing, and in general, localization is enhanced with bilateral processing. The central auditory centres analyze the acoustic input for subtle differences in intensity, the spectrum of the signal, and timing. There are three primary areas of localization: the direction of a sound from around us, or horizontal angle; the elevation of a sound source, or vertical angle; and the distance of a sound source.

Given that audibility is an important component of localization, it might seem that simply providing audibility with hearing aids would restore localization to normal or near normal. This is sometimes true, but it is also possible for no improvement to be observed or in the worst case, aided localization can be poorer than unaided performance.

There are several reasons for limited performance with hearing aids on localization. Some hearing aid users have cochlear distortions or cognitive deficits that will still be present. The factors associated with the hearing aids themselves include unbalanced gain, or in some cases a person with a bilaterally symmetrical hearing loss will be fitted with only one hearing aid which makes localization worse. Features such as compression, noise reduction and directional microphone technology, group delay, phase delay in digital hearing aids alter the timing of the signal.

Need for the study

Literature reveals that high frequency acoustic information is more critical for understanding speech and that individual with sensorineural hearing loss most often have greater loss in the high frequencies. The frequency response through a hearing aid is manipulated in frequency lowering technologies such as frequency transposition and frequency compression hearing aids. Since the frequency response through a hearing aid is manipulated in frequency compression hearing aids, the auditory skills (such as localization, speech perception in noise) that are influenced by the manipulation of frequency composition of the signal also get affected. Since there is a dearth of literature on these aspects of frequency compression hearing aids, the present study is being undertaken.

Aim and objectives of the study

The focus of the study is to find the effect of frequency compression on auditory performance of an individual with hearing impairment. The specific objectives include evaluating the effect of frequency compression on speech identification in noise and on localization.

CHAPTER2

REVIEW OF LITERATURE

In adults with hearing loss, high-frequency sensorineural hearing impairment is the most common configuration(Coletta, 2011). Ross (2009) is of the opinion that people with this type of problem, they often complain of hearing but not understanding, especially in the presence of noise. He attributes inaudibility of many of the high frequency voiceless consonants, such as the /t/, /k/, /f/, /th/, /sh/, and /s/ sounds as a primary reason for this. A popular way of management of such impairments is recommendation of hearing aids, which will have benefits as well as pitfalls.

The difficulty in providing sufficient amplification to the higher frequencies due to the possibility of cochlear dead regions and the upper frequency limits of hearing aids led to the concept of hearing aids that would shift the high frequencies of speech to the lower ones, i.e., frequency lowering technique (Kuk, Keenan, Auriemmo&Korhonen, 2009). The reasoning was that if the speech energy in the high frequencies could somehow be shifted to the lower frequencies, where the hearing thresholds were better, then this high-frequency information would at least be audible, though considerably modified and sounding somewhat “unnatural” (Ross, 2009).

Ross (209) has reviewed different techniques for frequency lowering in hearing aids. There are different techniques for frequency lowering in hearing aids. Dynamic Speech Recoding or Frequency Compression in hearing devices compress the entire spectrum and shift the high frequencies to the lower frequencies. All energy peaks within the signal are shifted proportionately (for example, with a frequency compression ratio of 2, sounds at 6000 Hz are shifted to 3000 Hz, while 3000 Hz sounds are moved to 1500 Hz and so on).

The second of such techniques is the Audibility Extender (AE) feature that transposes the unaidable high- frequency sounds to usable low-frequency regions. The hearing aid selects a “start” frequency, at which the AE program determines (based on the person’s stored thresholds) that aidable hearing ends and unaidable begins. For example, 2000 Hz could be the start frequency for someone whose thresholds drop off sharply at this frequency and whose hearing, therefore, is not usable above this point. The program then identifies a peak frequency within the non-aidable octave above the start frequency (in this case, from 2000 Hz to 4000 Hz), then shifts and filters it - and the sounds surrounding it - to fit in the octave below the start frequency (i.e., from 1000 Hz and 2000 Hz). It is important to properly identify the start frequency, a point the company stresses in its publications. If it is set too low, then usable hearing will not be aided normally; if set too high, then potentially important information will not be transposed.

The third technique in the frequency-lowering realm is the SoundRecover (SR) feature in hearing aids. This combines aspects of the two previous devices in that it both compresses high-frequency signals and shifts them to a lower-frequency region. The SoundRecover (SR) feature compresses speech signals above some pre-selected cut-off frequency and shifts this high frequency sound into a frequency region in which there is usable residual hearing. For example, the cut-off frequency was 2900 Hz and the compression ratio was 4:1means that all the speech energy above this frequency (extending to the limits of the hearing-aid response) would be divided by four and shifted to the area slightly higher than 2900 Hz (at which there was still usable residual hearing). The idea is to ensure that the important information contained in the very high frequencies is available to the hearing aid user. The selected cut-off frequency and compression ratio both depend upon the user’s hearing loss and may be modified to reflect a person’s listening experiences.

Frequencies lower than 2900 Hz (in this example) would be amplified as they would be normally.

Yet another technique is the FCo (Non-linear frequency compression). This leaves the lower part of the frequency spectrum untouched. This helps in retaining the information contained in the speech signal up to approximately 1500 Hz as this is required to extract speech information such as fundamental frequency (crucial for e.g. male vs. female voice distinction, meaning in tonal languages, prosody changes) and 1st and 2nd formantinformation (crucial for e.g. vowel and voiced consonant recognition). Contaminating this informationwould dramatically reduce speech intelligibility (SI) and sound quality for the patient. In FCo, a frequency is chosen from where the compression is required, the remaining part of the spectrum (from Fmin up to Fend) is non-linearly compressed into a narrower frequency range (Serman, Hannemann, &Kornagel, 2012).

A period of adaptation regardless of the technique used is required for realizing more benefits from such techniques. A large degree of individual variation can be expected. For reasons not fully understood, some people seem to benefit more than others. Children, perhaps because of much greater neural plasticity, seem to benefit more than adults (Ross, 2009).

The present study focused on evaluation of the effect of new technology in hearing aid, frequency compression on localization and speech identification in noise in individuals with sloping sensorineural hearing loss. The review has been into

2.1. Speech identification in noise

2.2. Localization.

2.1**. Speech identification in noise:**

Literature differs on the importance of frequencies above 2000 Hz for speech. In studying noise induced hearing loss, research has shown that thresholds at 3000 Hz and above are not significantly related to the hearing and understanding of everyday speech (Glorig, ward & Nixox, 1961; Quiggle, Glorig, Delk, & Summerfield, 1957). On the other hand, other researchers (Harris, Haines, & Myer, 1960; Kryter, Williams, & Green, 1962; Mullins & Bangs, 1957) have found that information in the frequencies above 2000Hz to be significant for understanding speech in the presence of noise. Pascoe (1975) suggested that the critical range of frequencies which have a significant effect on word recognition, particularly in noise, are those between 2500 and 6300 Hz.

Effect of sensorineural hearing loss in adults tend to have greatest amount of hearing loss in the higher speech frequencies (above 2000Hz), which generally corresponds to more extensive pathophysiological changes in the corresponding region of inner ear (Lieberman &Dodds, 1984; Willott, 1991). It is well established that in individuals with sensory neural hearing loss, suprasegmental features are perceived better than segmental features, vowels better than consonants, vowel height better than vowel position (front and back), word initial consonants better than word final consonants, and consonant voicing and continuance better than consonant place (Erber, 1972; Martony, Risberg, Spens, &Angelfors, 1972; Bilger& Wang, 1976; Hack &Eber, 1982).

Adult listeners with normal hearing seem to make more use of spectral cues for place of articulation information (Harris, 1958; Hedrick &Ohde, 1993; Heinz & Stevens, 1961; Hughes & Halle, 1965; Nittrouer, 2002; Zeng& Turner, 1090) and temporal information for the voicing distinction (Raphael, 1972; Cole & Cooper, 1975; Soli, 1982). Listeners with hearing impairment may have difficulty integrating amplitude and spectral cues, and may generally place less weight on formant transitions than listeners with normal hearing (Hedrick, 1997; Hedrick & Younger, 2003; Zeng& Turner, 1990).

Hogan and Turner (1998) evaluated the effects of hearing loss configuration and severity as well as the frequency bandwidth that maximized speech recognition scores. Speech recognition was tested at various band pass settings for five listeners with normal hearing and nine individuals with varying degrees of high frequency hearing loss. The test stimuli were presented through a Sennheiser HD 25-SP earphone with a supra-aural cushion. Results for the listeners with normal hearing demonstrated an increase in speech recognition scores as audibility increased. Results for the listeners with mild high frequency loss were similar to the listeners with normal hearing. Whereas results for listeners with moderate high frequency loss were poorer than those obtained from either the listeners with normal hearing or listeners with mild hearing loss.

Benefits of amplification were significantly more decreased when the degree of loss exceeded 55dB HL and the hearing loss fell in regions beyond 4 KHz as compared to when the hearing loss fell in regions below 5 kHz.(Augustana, 2001)

Overall results of various studies suggest that restoring of high frequency information to person with high frequency sensory neural hearing loss provides limited benefit to speech understanding. Based on these limited benefits, one recommendation may be to provide minimal or no amplification in some high frequency regions when greater hearing loss is present. There are a number of studies that make different claims about the effect of high frequency amplification. Byrne (1986) reported that listeners with sloping high frequency hearing loss judged the amplification providing the most extended high frequency emphasis to be the poorest in intelligibility. Most of the hearing instruments used in the study failed to amplify beyond 3 kHz.

Sullivan, Allsman, Nielsen, and Mobley (1992) speculated the increase in speech recognition for listeners with flat configurations was contributed to greater gain in the high and mid frequencies rather than simply amplification beyond 3 kHz. Without amplification, listeners with sloping losses were already receiving the maximum mid-frequency speech cues plus some high frequency speech cues. With amplification, listeners received only additional high frequency speech cues which resulted in little to no improvement in speech recognition scores. Without amplification, listeners with flat configurations received some mid frequency and high frequency speech cues. With amplification, listeners with flat configurations received additional mid frequency and high frequency speech cues which resulted in a significant improvement in speech recognition scores. Stated differently, with amplification, listeners with sloping losses were receiving high frequency speech cues, whereas, listeners with flat loses were receiving speech cues in the high frequencies as well as the low to mid frequencies. Therefore, Sullivan, Allsman, Nielson, and Mobley (1992) concluded that studies suggesting speech recognition scores improved due to high frequency amplification are questionable.

The management for individuals with sloping high frequency hearing loss is a challenging task. The conventional solution for individuals with a sloping audiometric pattern is a hearing aid with a frequency-gain response that improves audibility of high-frequency speech cues. However, even within a given frequency band, speech levels vary by at least 30dB (Fletcher, 1955; Skinner, 1988). This range is considerably increased by the variety of sound levels in different listening situations. For listeners with sloping loss, this variation is speech levels, couples with a reduced high-frequency dynamic range, may limit the ability to restore audibility without discomfort or distortion from higher level speech.

2.2 Localization:

According Flamme (2002), regarding localization the primary problem seen with is long delay times is destructive interference between the acoustic signal that passes by the hearing aid and the amplified sound. For some amounts of delay, the interference could move into frequency regions where the audibility of localization cues is reduced. The delay times might not be bilaterally matched, either because of a unilateral fitting or because of mismatched delays for bilateral hearing aid users. However, if the mismatch in delay time does not change often, people adapt to new interaural time difference cues over a period of hours or days.

Perreau, Bentler, and Tyler (2013) studied the contribution of a frequency-compression hearing aid to contralateral cochlear implant performance. The first experiment investigated the contribution of a frequency-compression hearing aid to contralateral cochlear implant (CI) performance for localization and speech perception in noise. The second experiment assessed monaural consonant and vowel perception in quiet using the frequency-compression and conventional hearing aid without the use of a contralateral CI or hearing aid. Ten subjects fitted with a cochlear implant and hearing aid participated in the first experiment. Seventeen adult subjects with a cochlear implant and hearing aid or two hearing aids participated in the second experiment.Histories of post lingual deafness were taken of a moderate or moderate-to-severe hearing loss who were not used to frequency-lowering hearing aid previously. In the first experiment, performance using the frequency-compression and conventional hearing aids was assessed on tests of sound localization, speech perception in a background of noise, and two self-report questionnaires. In the second experiment, consonant and vowel perception in quiet was assessed monaurally for the two conditions. In both experiments, subjects alternated daily between a frequency-compression and conventional hearing aid for 2 months. The parameters of frequency compression were set individually for each subject, and audibility was measured for the frequency compression and conventional hearing aid programs by comparing estimations of the Speech Intelligibility Index (SII) using a modified algorithm (Bentler et al., 2011). In both experiments, the outcome measures were administered following the hearing aid fitting to assess performance at baseline and after 2 months of use. Results revealed that no significant difference between the frequency-compression and conventional hearing aid on tests of localization and consonant recognition. Spondee-in-noise and vowel perception scores were significantly higher with the conventional hearing aid compared to the frequency-compression hearing aid after 2 months of use. These results suggest that, for the subjects in their study, frequency compression is not a better bimodal option than conventional amplification. In addition, speech perception may be negatively influenced by frequency compression because formant frequencies are too severely compressed and can no longer be distinguished.

Multichannel compression amplification offers an attractive option for improving speech audibility in listeners with sloping loss. When speech varies over a range of input levels, the compression can improve recognition by placing greater amounts of the speech signal in the range between threshold and discomfort (Moore &Glasberg, 1986; Souza & Turner, 1998). Use of more than one compression channel allows the audiologist to maximize audibility by accommodating variations in threshold and dynamic range across frequency. However, maximizing audibility in the regions of greater loss (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998).

To overcome the difficult, that most of the individuals with hearing loss have poorer thresholds at the high frequencies when compared to low frequencies had led to the development of Frequency lowering technology, the main objective is to make use of better thresholds at lower frequencies to improve the audibility of high frequency information hearing components of speech. The information conveyed by the high frequency may be perceived as a lower frequency substitute. The addition of this information, along with the intact low mid frequency information, should improve the audibility of sounds for individuals using transposition device over conventional amplification (Kuk, Keenan, Peeters, Korhonen, Hau, & Anderson, 2007).

It is possible that frequency lowering can improve the ability of some listeners to perceive details of spectral shape, perhaps resulting in better speech intelligibility. This benefit may be obtained if the broadening of auditory filters, which usually accompanies sensory neural hearing loss, is not as extensive at low frequencies as at high frequencies.

Main types of frequency lowering technology:

Frequency transposition: the basis of this is the high frequency signal is transposed or moved down to some other frequency region where it is more able to analyze signal. By providing a representation of high frequency sounds which would otherwise be inaudible, it is anticipated that improvements may occur in speech perception and intelligibility in individuals with high frequency sensory neural hearing loss as it provided additional cues for the discrimination of speech. When the right candidates are chosen and when specific guidelines are followed, frequency transposition provides a viable solution for adults and children with an unaidable hearing loss in the high frequencies (Kuk, Keenan, Peeters, Korhonen, Hau, & Anderson, 2007).

In frequency compression signal processing strategy, there is proportional compression of high frequency signal into lower frequency ranges by reducing the bandwidth and frequency of the signal. Proportional frequency compression attempts to preserve the relationship of the high frequency energy peaks while leaving low frequency information uncompressed but amplified. For these users both the hearing level at specific frequencies and the slope of the audiogram across frequencies are taken into account. for cut-off frequency, relatively high frequencies are selected, if the hearing impairment is mild or the audiogram is flat. The lower cut-off frequencies are selected for more severe levels of impairment or for audiograms with relatively steep slopes. The higher the degree and steepness of hearing loss, lesser the cut off frequency and more is the degree of frequency compression that is applied.

Studies have shown that Non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses. (Simpson et al., 2006; Bohnert, Nyfellar, &Keilmann, 2010). McDermott et al. (1999) examined performance in a group of five adults fit monaurally with the same FC device. In a 12 week period, it was noted that the FC did significantly improve the recognition of HF phonemes for two of the five individuals. However for two individuals, sentence test results were significantly improved over their own hearing aids not because of the frequency lowering but because of the low frequency amplification.

McDermott and Knight (2001) reported that consonant identification scores were the same for the Linear frequency transposition (LFT)-on and the LFT-off conditions. However, a significant improvement in consonant identification scores was obtained after training.

Swapna and Rajalakshmi (2007) studied the efficacy of frequency transposition hearing aid in subjects with dead regions. In the study, it was found that with frequency transposition there was significant amount of benefit than without it. Hrishikesan and Manjula (2009) studied the efficacy of non linear frequency compression in individuals with and without cochlear dead regions. The results revealed that there was a significant difference in the mean SIS scores without NLFC and NLFC fine tune setting for individuals without cochlear dead region. There was no significant difference in individuals with cochlear region ling's six sound identification reveal a slight improvement in fricative identification among participants without cochlear dead region only. The results of quality rating showed that the mean rating of quality were higher for individuals without cochlear region compared to those with cochlear dead region.

Anjana and Geetha (2011) studied the utility of non linear frequency compression on detection and speech identification abilities in quiet and in presence of noise, in children with severe to profound hearing loss who have limited or no benefit from high frequency amplification. Results revealed NLFC benefits for detecting high frequency tones. Identification of words also showed significant benefit from NLFC in quiet and in the presence of noise.

As there are evidences regarding the usefulness of high frequency amplification in individuals with high frequency sensorineural hearing loss, there is a need to validate the effect of frequency compression on speech identification in noise and on localization.

CHAPTER 3

METHOD

The present study focused on evaluating the effect of frequency compression on speech perception in noise and on localization in individuals with sloping sensorineural hearing loss, under two aided conditions - without frequency compression and with frequency compression.

Participants

The present study incorporated 20 ears of 10 individuals with bilateral sloping sensorineural hearing loss. The slope considered was gradual 10 – 15 dB per octave from 2 k Hz. The participants were native speakers of Kannada in the age range from 15 to 55 years. The degree of hearing loss ranged from moderately severe to profound sensorineural hearing loss. All participants were naive hearing aid users, except two who were experienced hearing aid users. There participants were not having any middle ear pathology as revealed by immittance evaluation. Further, participants with any complain of neurological or cognitive problems were also excluded from the study.

Test material

The Phonemically Balanced Word list (Yathiraj&Vijayalakshmi, 2005) and high frequency word list (Mascarenhas, 2001) were used for speech identification. The PB word list consisted of four lists of 25 bi-syllabic words each. The high frequency word lists consisted of three lists with words having speech sounds predominantly above 2 kHz. Thirty-two trains of white noise burst were used to evaluate the localization ability.

Instrumentation

A calibrated diagnostic sound field audiometer (MADSEN, ORBITER, 922) was used to administer pure-tone audiometry, speech audiometry and aided performance. A calibrated immittance meter (GrasonStadler Incorporated Tympstar) was used for ruling out middle ear pathology. Two digital BTE hearing aids with 6 channels, Sound Recover feature (Frequency compression between 1.5 kHz to 6 kHz), gain of 80 dB SPL, MPO of 141 dB SPL were used. The HiPro connected to a personal computer with NOAH software and default hearing aid programming software was used to program the hearing aid.

For localization eight loudspeakers connected to a personal computer with CuBase 6 software was used. The loud speakers (Genelec 8020B speakers) were mounted on Iso-

Pod™(Isolation position/decoupler™) vibration insulating table stand and were located at 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, and 315^o Azimuth covering a range of 0^o to 360^o. The loud speakers were arranged in a circular array with one meter radial diameter from centre.

White noise stimulus generated using Adobe Audition 3.0 on the computer was routed through these speakers. The output of each loud speaker was calibrated using a Larson-Davis system 824 Sound Level Meter (model no. 2540) placed at centre with a ½ inch free-field microphone. The microphone of the sound level meter with preamplifier was placed at a position corresponding to the centre of the head and at a height of one meter. The sound pressure level readings were taken by presenting the noise burst stimuli of 30 second duration through each of the loudspeakers.

Hearing aid programming

The data for the present study were collected in aided condition. The test hearing aids were programmed by connecting them to the HiPro which in turn was connected to the personal computer with software for hearing aid programming. The hearing aid was programmed using the auditory thresholds of the participants and the proprietary fitting formula. Audibility of Ling's six sounds was done for optimization of the gain provided to each ear of each participant.

Two programs were enabled for each ear, Program 1 was set with frequency compression (FC) feature disabled, and Program 2 was set with frequency compression (FC) enabled.

Procedure

All the testing was carried out in an air-conditioned sound treated single or double room set-up. The data were collected in two phases. Phase I included collection of data on speech identification in noise (SNR-50) in monoaural aided condition. Phase II included collection of data on localization in binaural aided condition.

Phase I.

This stage incorporated measurement of speech identification in Noise (SNR-50).The task was to measure the speech identification in the presence of noise through the SNR-50 measure. This was done in the aided condition without and with FC. The participants were instructed to repeat the words presented in the presence of noise. They were also informed that the level of speech would remain constant and that of noise would be varied.

The participant was made to wear the hearing programmed aid on the test ear coupled using an eartip. The hearing aid was set to P1 and later changed to P2 program setting. He/she was seated on ca chair comfortably in the patient room, at a distance of one meter and an angle of 0^0 Azimuth from the loudspeaker. The PB words list (Yathiraj&Vijayalakshmi, 2005) was presented in live mode by a native Kannada speaker at 45 dBHL, with VU monitoring.

Signal to noise ratio-50 (SNR-50) was used to measure the speech identification in noise performance. For the measurement of SNR-50, the level of speech was kept constant at 45 dB HL. The initial level of speech noise was 30 dB HL. The level of noise was increased initially in 5 dB steps (later in 2 dB steps) till the participant repeated 50% of the words being presented. Three words were presented at each level of speech noise. This was done to find out the highest level of speech noise at which the participant could repeat 50% of the words. At this point, the difference in the level of speech and speech noise was noted as the SNR-50.The above procedure was used to measure the SNR-50 for PB word list and HF word list (Mascarenhas, 2001), in two aided conditions (without and with FC).

Phase II.

This stage consisted of localization experiment. The task was to point to the direction from where the noise burst was presented. The noise burst stimuli was presented randomly four times with an inter stimulus interval of 5 seconds. The noise bursts were presented from each of the eight loud speakers located at different azimuths, from 0^o to 360^o A at 45^o intervals.

The participant was seated at the centre, i.e., equidistant from the eight loud speakers. The participants were instructed to point to the loud speaker from where they hear the train of noise burst. A set of stimuli for localization consisted of 32 trains, each train consisted of 4 white noise bursts. The response of the participant was noted in terms of the loud speaker from which he/she thought that the sound arrived with respect to the loud speaker through which the sound was actually presented. The difference between the target loud speaker and the response was utilized to compute the degree of error (DOE) for localization.

The DOE corresponds to the difference in degrees between the degrees of azimuth of the loudspeaker of actual presentation of the stimuli, to the degree of azimuth of the loudspeaker identified as the source of the stimulus by the participant. For example, if the stimulus was presented from a loudspeaker at 45^0 azimuth and the participant reported the sound to be arriving from loudspeaker at 315^0, then the degree of error would be 90^0 i.e., 45^0-(315^0) = 90^0. This DOE was obtained for 8 trials in each aided condition. Thus, in each of the two aided conditions, there was a set of eight degrees of errors. The formula for calculating the root mean square DOE (Ching, Incerti, & Hill, 2004) is given below.

$$\text{rms DOE} = \sqrt{\frac{(DOE)_1^2 + (DOE)_2^2 + (DOE)_3^2 + \ldots + (DOE)_8^2}{8}}$$

Where, $DOE_{1\text{-}8}$= Degree of Error of the eight loud speakers; and

rms DOE = Root mean square degree of Error.

This procedure was used to measure the localization in two aided conditions, without FC and with FC. For each participant, the DOE for localization from each loud speaker, Front (0^o, 45^o and 315^o), back (135^0, 180^0 and 225^0), right (45^0, 90^0 and 135^0) and left (225^0, 270^0

and 315^0) localization were also computed. This was done by averaging the DOE for corresponding number of loud speakers.

In the present study, for each test ear, the SNR-50 was obtained. In addition, for ear individual, DOE of localization for eight loud speakers, front, back, right and left loudspeakers were obtained. The data were tabulated subjected to statistical analysis using Statistical Package for Social Sciences statistics 17 (SPSS). Descriptive statistics and Analysis of variance using non-parametric statistics were carried in order to find out the effect of frequency compression on SNR-50 and localization.

CHAPTER4

RESULTS AND DISCUSSION

The study was conducted with the aimof evaluating the effect of frequency compression (FC) in hearing aids on speech identification in noise (SNR-50) and localization, in individuals with sloping sensorineural hearing loss.

The data collected on SNR-50 (for PB and high frequency words) and localization in two aided conditions (i.e., without frequency compression and with frequency compression) were tabulated and analyzed using Statistical Package for Social Sciences version 17 (SPSS). The statistical tools used to measure are descriptive statistics and analysis of variance.

The data were collected from 10 individuals with sloping sensorineural hearing loss. The parameters measured were SNR-50 for speech perception in noise, and root mean square degree of error (rmsDOE) for localization.

The results are discussed under the following headings:

4.1 SNR-50

4.2 Localization.

4.1 SNR-50 for Phonemically Balanced (PB) words and High Frequency (HF) words:

The mean and standard deviation (SD) of SNR-50 collected from 20 ears (10 right and 10 left) of 10 subjects for phonemically balanced and high frequency words are provided in Table 4.1.

Table 4.1

Mean, median and standard deviation (SD) of SNR-50 for PB words and HFwords.

		SNR-50 in dB					
Ear	*Aided condition*	*PB words*			*HF words*		
		Mean	*Median*	*SD*	*Mean*	*Median*	*SD*
Right *(N=10)*	Without FC	1.60	2.0	2.12	4.7	4.0	3.47
	With FC	-1.30	-2	2.06	-1.4	-2.5	2.55
Left *(N=10)*	Without FC	2.50	3	3.14	3.4	3.5	2.91
	With FC	-0.5	-1.5	2.95	-2	-2.5	2.87

Note: ‘dB’: Decibel; ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘SD’: Standard Deviation; ‘FC’: Frequency Compression; ‘N’: Number of subjects

From Table 4.1 and Figure 4.1, it can be noted that the mean SNR-50 was lower in the aided condition with frequency compression indicating better performance in this condition, compared to the condition without the FC.This means that the performance is better in the aided condition with FC since the participants repeated 50% of the words even when the difference between the speech and speech noise was lesser. Further, the performance for the PB words was better compared to the HF words. The median values are also depicted in the tableas the standard deviation values indicated high variability.

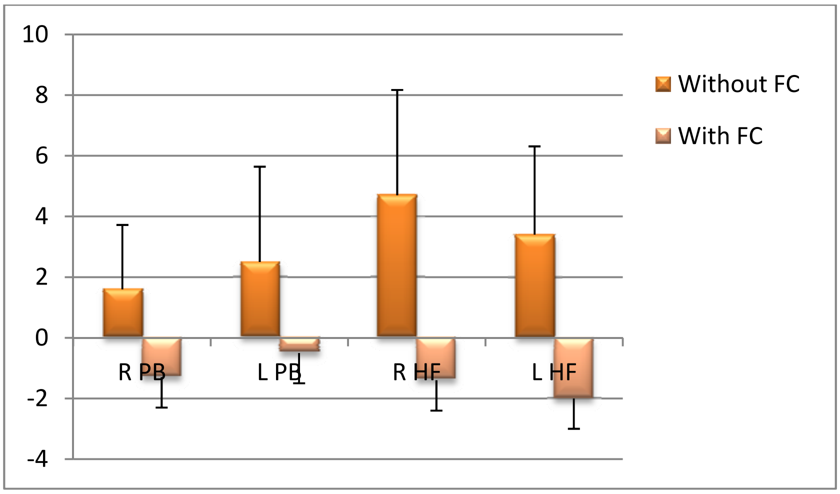

*Figure 4.1.*Box plot of mean and standard deviation of SNR-50 for PB words and words in right and left ears, without frequency compression (FC) and with frequency compression (FC)

The Wilcoxon signed ranks test was performed inorder to see if there was a significant difference in SNR-50 between the right ear without FC and left ear without FC, and between the right ear with FC and left ear with FC. This was done with an intention of grouping the right and left ear scores if there was no significant difference between their scores.

Table 4.2

Results of Wilcoxon's signed rank test for right and left ear SNR-50 values

Aided Conditions	*SNR-50*			
	PB Words		*HF words*	
	Z	*P*	*Z*	*P*
Right-Left (Without FC)	-1.022	0.307	-0.921	0.357
Right-Left (With FC)	-1.14	0.254	-1.027	0.305

Note: 'HF': High Frequency; 'SD': Standard Deviation; 'FC': Frequency Compression; 'N': Number of subjects

The test revealed that there was no significant difference between the right and left ears in the two aided conditions (i.e., without and with FC). Hence, the SNR-50 values of the right and left ears were grouped together, for the two aided conditions. Table 4.3 and Figure 4.2 provide the mean, median and SD of the SNR-50 for PB and HF words when the SNR-50 valuesof the two ears were combined, in the two aided conditions.

Table 4.3

Mean, median and SD of SNR-50 (in dB) for PB and HF words, in the two aided conditions (without FC and with FC).

Aided Conditions (N=20)	*Stimuli*	*SNR-50 in dB*		
		Mean	*Median*	*SD*
Without FC	PB words	2.05	3.00	2.37
	HF words	4.05	5.00	2.78
With FC	PB words	-0.90	-1.25	2.25
	HF words	-1.70	-2.00	2.59

Note: ‘dB’: Decibel; ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘SD’: Standard Deviation; ‘FC’: Frequency Compression; ‘N’: Number of subjects

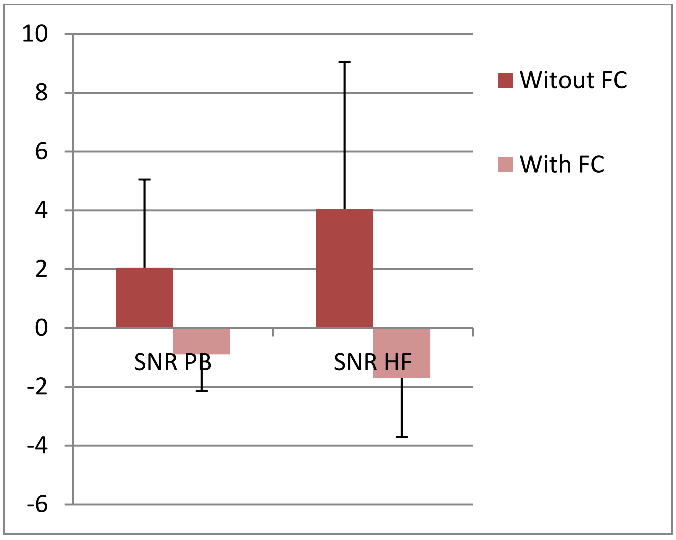

Figure 4.2. Box plot showing the mean and SD of SNR-50 for PB and HF words in the two aided conditions

From the Figure 4.2, it can be noted that the performance for both PB and HF words was better in the aided condition with FC compared to without FC. To examine if this difference in the aided conditions was significant, Wilcoxon’s signed ranks test was done. This test (Table 4.4) revealed that there was no significant difference between the SNR-50 in the two aided conditions (without FC and with FC), for both PB and HF words.

Table 4.4

Results of Wilcoxon’s signed rank test for SNR-50 values in the two aided (without FC and with FC) conditions

<table>
<tr><th rowspan="3">AidedConditions</th><th colspan="4">SNR-50</th></tr>
<tr><th colspan="2">PB words</th><th colspan="2">HF words</th></tr>
<tr><th>Z</th><th>p</th><th>Z</th><th>p</th></tr>
</table>

Without FC –With FC	-2.494	0.013	-2.810	0.005

Note: ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘FC’: Frequency Compression;

From Tables 4.3 and 4.4, it is evident that the SNR-50 performance was significantly better in the aided condition with FC compared that condition without FC. Hence, it can be inferred that the FC provides benefit in speech understanding in the presence of noise.

In literature, there are reports stating that frequency compression does not make a difference in performance compared to conventional amplification (Anna, Ingrid, Hartley, Lisa, Gitte, &Myriel, 2010) or that the frequency compression improves performance (Simpson et al., 2006); Bohnert, Nyfellar, & Keilmann,2010; McDermott et al., 1999). There are reports which support the results of the present study.

Simpson et al. (2006), Bohnert, Nyfellar, and Keilmann (2010) have shown that non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses. McDermott et al. (1999) noted that the FC did significantly improve the recognition of HF phonemes for two of five individuals who were fittedwith FC devicemonaurally, when evaluated after a 12 week period. Swapna and Rajalakshmi (2007) found that there was a significant benefit with frequency transposition than without it, in subjects with dead regions. Hrishikesan and Manjula (2009)have also found significant better performance on speech identification with non-linear frequency compression (NLFC),in individuals without cochlear dead region. They also noted that the performance was better when the NLFC was optimized for individual participant. Anjana and Geetha (2011) obtained NLFC benefits for detecting high frequency tones. Identification of words also showed significant benefit from NLFC in quiet and in the presence of noise.

4.1 Localization

Localization in horizontal plane was measured at eight azimuths, i.e., 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o with the participant wearing binaural hearing aids, in FC enabled and disabled conditions. The root mean square degree of error (rmsDOE) is calculated for each angle that was included in the study 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o. Further, the rmsDOE was also compared for right, left, front, back and overall localization were also evaluated.

Table 4.5

Root mean square degree of error (rmsDOE) in localization of eight different angles.

		rmsDOE								
Aided Condition	*Stat measure*	*0^0*	*45^0*	*90^0*	*135^0*	*180^0*	*225^0*	*270^0*	*315^0*	*Overall*
Without FC	Mean	60.75	21.38	36.0	40.25	1.13	37.13	11.25	3.37	40.96
	Median	56.25	11.25	11.25	32.50	0	22.50	5.63	0	31.57
	SD	49.52	25.13	43.67	34.92	6.39	58.59	19.12	15.95	24.81
With FC	Mean	48.38	9.00	7.88	25.88	0	5.63	2.25	2.25	25.72
	Median	33.75	5.63	0	11.25	0	11.25	0	0	24.19
	SD	56.39	13.83	21.89	27.07	0	10.93	24.19	32.17	22.33

Note: ‘dB’: Decibel; ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘SD’: Standard Deviation; ‘FC’: Frequency Compression; ‘N’: Number of subjects

From Table 4.5, it can be observed that in the aided condition without FC, the rms DOE was highest at 0^0 followed by 135^0, 225^0, 90^0, 45^0, 270^0, 315^0 and 180^0. In the aided condition with FC too, a similar pattern was noted except at $45^0$and 225^0. Figure 4.3 also depicts the same.

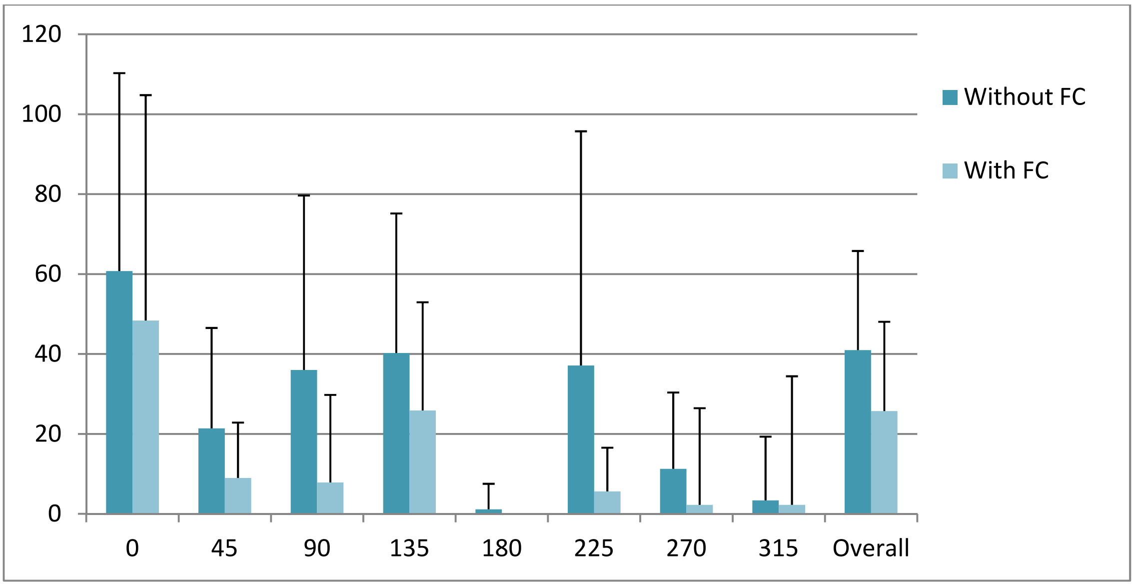

Figure 4.3 Box plot of mean and SD of the rms DOE without FC and with FC, at eight different angles

The rmsDOE were higher in the aided condition without FC compared to with FC condition, indicating that localization was facilitated by FC in the hearing aid. This could be because, the high frequency audibility was increased with FC compared to without FC condition. In order to know if there was a significant difference between without FC and with FC conditions, Wilcoxon signed ranks test was administered. This revealed that there was a significantly better performance with FC compared to without FC at 0^0, 45^0, 90^0, 135^0, and 225^0angles (Table 4.6). The overall localization ability (mean performance of eight different angles) was also significincly better with FC compared to without FC condition.

Table 4.6.

Results of Wilcoxon Signed Ranks test for localization of eight angles for two conditions.

Angles in Degrees	*Z*	*p*
0	-1.261	0.207
45*	-2.456	0.014
90*	-2.414	0.016
135*	-2.032	0.042
180	-.577	0.564
225*	-2.201	0.028
270	-1.276	0.202
315	.000	1.000
Overall*	-2.803	0.005

Note: *: significant difference at 0.05 level

The mean and SD of root mean square degree of error in the horizontal plane localization from front, back, right and left is given in Table 4.7. It can be observed that in the aided condition without FC, the rms DOE was highest at right followed by front, back and left sides. In the aided condition with FC too, the rms DOE was the highest from front followed by right, back and left. Figure 4.4 also depicts the same. Further, the variability in rmsDOE was in higher without the FC condition as revealed by the SD.

Table 4.7.

Mean, median and SD of rms DOE in front, back, right and left localization

Aided Conditions		*Localization*			
		Front	*Back*	*Right*	*Left*
Without FC	Mean	28.50	26.17	32.54	17.25
	Median	24.38	15.0	26.25	7.5
	SD	28.41	26.03	30.97	26.29
With FC	Mean	15.0	7.13	13.88	1.13
	Median	7.5	1.88	7.5	3.75
	SD	31.62	11.79	18.20	18.63

Note: 'SD': Standard Deviation; 'FC': Frequency Compression; 'N': Number of subjects

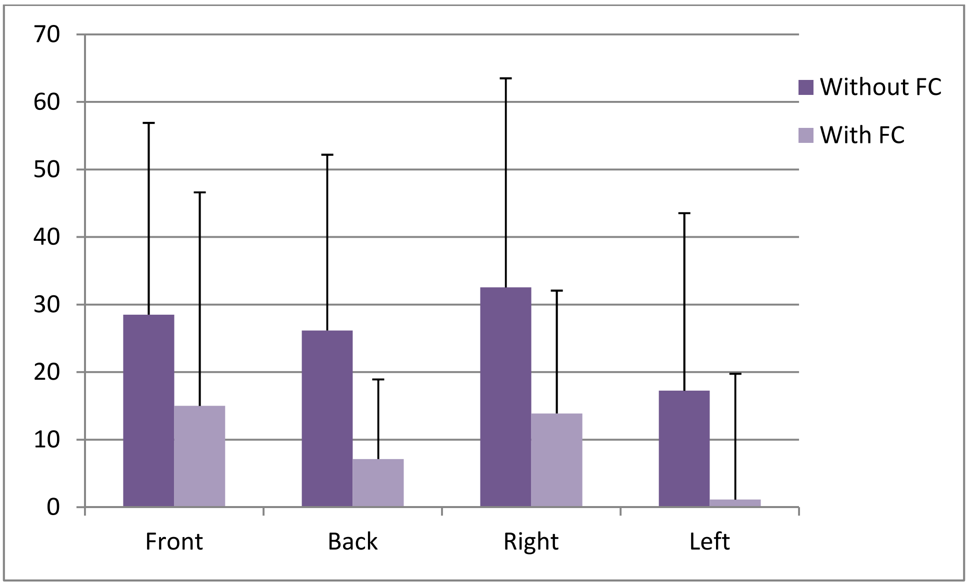

*Figure 4.4.*Box plot of mean and SD of the rms DOE in localization of front, back,right and left sides, without FC and with FC

Further, the rms DOE were higher in the aided condition without FC compared to with FC condition, indicating that the localization was facilitated by FC in the hearing aid. In order to know if there was a significant difference between the without FC and with FC conditions, Wilcoxon signed ranks test was administered(Table 4.8). This revealed that there was a significantly better performance with FC compared to without FC at all directions, i.e., front, back, right and left. The overall localization ability (mean performance of eight different angles) was also significantly better with FC compared to without FC condition. This is because thefrequency compression increases the audibility of high-frequency localization cues.

Table 4.8.

Wilcoxson test result for significant difference between with and without FC conditions

Localization with and without FC	*Z*	*P*
Front	-2.655	0.008
Back	-2.451	0.014
Right	-2.670	0.008
Left	-2.103	0.035
Overall	-2.803	0.005

Note: ‘FC’: Frequency Compression

There are limited studies on localization using frequency compression technology. In the present study, it could be inferred that frequency compression helps in improving the performance on localization. The FC facilitated the audibility of high frequencies to a significant extent that the localization improved with FC compared to without FC. However, in the study by Anna, Ingrid, Hartley, Lisa, Gitte, and Myriel(2010), it was reported that there is no significant difference in localizationwith frequency compression ‘on’and‘off’ condition.The explanation provided by them was that though frequency compression increased audibility of monaural high-frequency front-back localization cues between 2000 and 5000 Hz, that they were spectrally compressed may have made them less usable.

The results reveal that better performance was observed in aided condition with FC enabled on speech identification in noise(SNR-50) for PB words & HF words andonlocalization (rmsDOE).

CHAPTER5

SUMMARY AND CONCLUSIONS

The present study focused on evaluating the effect of frequency compression on speech identification in noise and on localization in ten individuals with sloping sensorineural hearing loss, under two aided conditions - without frequency compression and with frequency compression (FC).

The study was conducted in two phases. In Phase I, Speech identification in noise (SNR-50) was measured and in Phase II, localization for eight angles was evaluated. The data collected on speech identification in noise, SNR-50 (for PB and high frequency words) and localization in two aided conditions (i.e., without FC and with FC) were tabulated and analyzed using Statistical Package for Social Sciences version 17 (SPSS). The statistical tools used to measure are descriptive statistics and analysis of variance. The results revealed that:

1. There was no significant difference in SNR-50 between the right and left ear in the two aided conditions (without FC and with FC). Hence, the data from the two ears were grouped together.
2. The speech perception in noise was better in the aided condition with FC enabled than when it was disabled. This was true for both PB words and HF words.
3. The benefit obtained from FC for HF words was more than for PB words, indicating that high frequency audibility was improved with FC.
4. In localization, the degree of error was less when the FC was enabled than when it was disabled. This could again due to the fact that the high frequency audibility improved with FC. There was significantly better horizontal plane localization for front, back, right and left in with FC compared to without FC condition.

It could be inferred from the results of the present study that the performance is better, in both speech identification in noise and localization, in the aided condition with FC enabled.

Clinical implications of the findings of the present study is that frequency compression in hearing aids helps an individual with sloping hearing loss to understand speech in noise and in localization.

Future directions for research:

a. This study can be further extended to find out the effect of frequency lowering more number of participants.
b. Further, this study can be extended to compare between conventional hearing aid and frequency lowering technology.

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CHAPTER 1

INTRODUCTION

Most individuals with sensorineural hearing impairment have a greater loss for high frequency sounds than for low frequency sounds. For some of them high frequency hearing loss is so great that they cannot extract any useful information from the high frequency sounds of speech. This occurs even if the speech is amplified sufficiently to be audible (Dillon, 2001). According to Dillon (2001) for sloping losses when high frequency thresholds are 70 dB HL or greater, the high frequency sounds of speech apparently contribute very little or no information; worse still for some of them making the high frequency parts of speech audible can decrease their ability to use information from the low- and mid- frequencies of the signal.

Literature has revealed that the most prevalent audiometric configuration among adults with hearing loss is the sloping type which is around 50% (Pittman &Stelmachowicz, 2003). Usually individuals with this type of audiogram configuration present with complaints of difficulty in understanding speech, especially in the presence of background noise. Hearing aid is the preferred form of management for such individuals.

American Speech Language Hearing Association (1998) has asserted that amplification should provide audibility and comfort for soft and average input levels, and tolerance for high input levels. The primary goal of current hearing aid fitting strategies is to make the speech signal audible in those regions where the sensitivity is reduced, and in the case of high frequency hearing loss this means providing high frequency amplification.

The bandwidth of conventional hearing aids is not broad enough to make high frequency sounds consistently audible for individuals with hearing loss (Stelmachowicz, Pittman, Lewis, & Hoover, 2003). This limits the audibility of important high frequency sounds, especially for individuals with a sloping and/or severe to profound hearing loss.

The need to provide audibility of high frequency information to listeners with greater hearing impairment is contentious (Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998; Plyler& Fleck, 2006; Turner & Henry, 2002). Larger variability in aided listening performance is thought to be due to both the level of high frequency audibility the listener is receiving as well as the ability of the listener to extract useful information from the audible signals.

There are equivocal reports in literature regarding the usefulness of high frequency amplification for individuals with sloping hearing loss. A few studies suggest that listeners who are provided with audibility at frequencies where hearing levels are severe and/or sloping will not show speech recognition benefit (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katch, & Byrne, 2001; Hogan & Turner, 1998). This is thought to be due to limited ability to use the amplified signal in the frequency region. On the other hand, other studies have reported that significant improvements in speech understanding especially in noisy environments occurs when listeners with sloping sensorineural hearing loss are provided with high frequency information (Plyler& Fleck, 2006; Turner & Henry, 2002).

To overcome the problem faced by individuals with a sloping hearing loss, frequency lowering technology is implemented in hearing devices. This shifts the high frequency components to a lower frequency range where audibility is more useful. This has been shown to improve the production and recognition of high frequency speech sounds for children and adults with severe to profound hearing loss (Auriemmo et al., 2009; Glista, Scollie, Bagatto, Seewald, Parsa, & Johnson, 2009; Kuk, Keenan, Korhonen, & Lau, 2009)

The two types of frequency lowering technology used in hearing devices include frequency transposition and frequency compression. In frequency transposition, the high frequency signal is transposed or moved down to lower frequency region where it is more able to analyse the signal. The frequency compression proportionally compresses high frequency signal into a lower frequency range by reducing the bandwidth and frequency of the signal. The latter attempts to preserve the relationship of the high frequency energy peak while leaving low frequency information uncompressed but amplified.

A few studies have been conducted to examine the use of frequency lowering technology (Miller-Hansen, Nelson, Wider, & Simon, 2003). Studies have shown that Non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses (McDermott, Dorkos, Dean, &Ching, 1999; Simpson, Hersbach, & McDermott, 2006; Hrishikesan&Manjula, 2009; Bohnert, Nyfellar, &Keilmann, 2010; Anjana&Geetha, 2011). Researchers have also reported beneficial effects of frequency transposition technique (McDermott & Knight, 2001; Raj &Rajalakshmi, 2007)

Transposing frequencies to a region one octave below the start frequency shifts the high frequency information to a lower frequency region where it may be utilized better (Moore, 2004). Additionally, temporal and spectral characteristics of the input signal below the start frequency are unaffected. In this manner, high frequency cues can be made available to the listener without introducing unnecessary distortion.

A hearing aid influences the performance of individuals in terms auditory skills such as speech audibility, speech identification, and localization. Apart from affecting the speech identification, the frequency lowering technique in hearing aids may influence localization. Localization is one of the major functions of the human ear and is a term used to describe the location of a sound source in the environment. This activity allows one to know the direction of the sound source in a three-dimensional space (Flamme, 2002)

The binaural cues have received a great deal of attention from researchers Flamme(2002). According to Fischer and Weber (2013) some aspects of auditory localization require bilateral processing, and in general, localization is enhanced with bilateral processing. The central auditory centres analyze the acoustic input for subtle differences in intensity, the spectrum of the signal, and timing. There are three primary areas of localization: the direction of a sound from around us, or horizontal angle; the elevation of a sound source, or vertical angle; and the distance of a sound source.

Given that audibility is an important component of localization, it might seem that simply providing audibility with hearing aids would restore localization to normal or near normal. This is sometimes true, but it is also possible for no improvement to be observed or in the worst case, aided localization can be poorer than unaided performance.

There are several reasons for limited performance with hearing aids on localization. Some hearing aid users have cochlear distortions or cognitive deficits that will still be present. The factors associated with the hearing aids themselves include unbalanced gain, or in some cases a person with a bilaterally symmetrical hearing loss will be fitted with only one hearing aid which makes localization worse. Features such as compression, noise reduction and directional microphone technology, group delay, phase delay in digital hearing aids alter the timing of the signal.

Need for the study

Literature reveals that high frequency acoustic information is more critical for understanding speech and that individual with sensorineural hearing loss most often have greater loss in the high frequencies. The frequency response through a hearing aid is manipulated in frequency lowering technologies such as frequency transposition and frequency compression hearing aids. Since the frequency response through a hearing aid is manipulated in frequency compression hearing aids, the auditory skills (such as localization, speech perception in noise) that are influenced by the manipulation of frequency composition of the signal also get affected. Since there is a dearth of literature on these aspects of frequency compression hearing aids, the present study is being undertaken.

Aim and objectives of the study

The focus of the study is to find the effect of frequency compression on auditory performance of an individual with hearing impairment. The specific objectives include evaluating the effect of frequency compression on speech identification in noise and on localization.

CHAPTER2

REVIEW OF LITERATURE

In adults with hearing loss, high-frequency sensorineural hearing impairment is the most common configuration(Coletta, 2011). Ross (2009) is of the opinion that people with this type of problem, they often complain of hearing but not understanding, especially in the presence of noise. He attributes inaudibility of many of the high frequency voiceless consonants, such as the /t/, /k/, /f/, /th/, /sh/, and /s/ sounds as a primary reason for this. A popular way of management of such impairments is recommendation of hearing aids, which will have benefits as well as pitfalls.

The difficulty in providing sufficient amplification to the higher frequencies due to the possibility of cochlear dead regions and the upper frequency limits of hearing aids led to the concept of hearing aids that would shift the high frequencies of speech to the lower ones, i.e., frequency lowering technique (Kuk, Keenan, Auriemmo&Korhonen, 2009). The reasoning was that if the speech energy in the high frequencies could somehow be shifted to the lower frequencies, where the hearing thresholds were better, then this high-frequency information would at least be audible, though considerably modified and sounding somewhat “unnatural” (Ross, 2009).

Ross (209) has reviewed different techniques for frequency lowering in hearing aids. There are different techniques for frequency lowering in hearing aids. Dynamic Speech Recoding or Frequency Compression in hearing devices compress the entire spectrum and shift the high frequencies to the lower frequencies. All energy peaks within the signal are shifted proportionately (for example, with a frequency compression ratio of 2, sounds at 6000 Hz are shifted to 3000 Hz, while 3000 Hz sounds are moved to 1500 Hz and so on).

The second of such techniques is the Audibility Extender (AE) feature that transposes the unaidable high- frequency sounds to usable low-frequency regions. The hearing aid selects a “start” frequency, at which the AE program determines (based on the person’s stored thresholds) that aidable hearing ends and unaidable begins. For example, 2000 Hz could be the start frequency for someone whose thresholds drop off sharply at this frequency and whose hearing, therefore, is not usable above this point. The program then identifies a peak frequency within the non-aidable octave above the start frequency (in this case, from 2000 Hz to 4000 Hz), then shifts and filters it - and the sounds surrounding it - to fit in the octave below the start frequency (i.e., from 1000 Hz and 2000 Hz). It is important to properly identify the start frequency, a point the company stresses in its publications. If it is set too low, then usable hearing will not be aided normally; if set too high, then potentially important information will not be transposed.

The third technique in the frequency-lowering realm is the SoundRecover (SR) feature in hearing aids. This combines aspects of the two previous devices in that it both compresses high-frequency signals and shifts them to a lower-frequency region. The SoundRecover (SR) feature compresses speech signals above some pre-selected cut-off frequency and shifts this high frequency sound into a frequency region in which there is usable residual hearing. For example, the cut-off frequency was 2900 Hz and the compression ratio was 4:1means that all the speech energy above this frequency (extending to the limits of the hearing-aid response) would be divided by four and shifted to the area slightly higher than 2900 Hz (at which there was still usable residual hearing). The idea is to ensure that the important information contained in the very high frequencies is available to the hearing aid user. The selected cut-off frequency and compression ratio both depend upon the user’s hearing loss and may be modified to reflect a person’s listening experiences. Frequencies lower than 2900 Hz (in this example) would be amplified as they would be normally.

Yet another technique is the FCo (Non-linear frequency compression). This leaves the lower part of the frequency spectrum untouched. This helps in retaining the information contained in the speech signal up to approximately 1500 Hz as this is required to extract speech information such as fundamental frequency (crucial for e.g. male vs. female voice distinction, meaning in tonal languages, prosody changes) and 1st and 2nd formantinformation (crucial for e.g. vowel and voiced consonant recognition). Contaminating this informationwould dramatically reduce speech intelligibility (SI) and sound quality for the patient. In FCo, a frequency is chosen from where the compression is required, the remaining part of the spectrum (from Fmin up to Fend) is non-linearly compressed into a narrower frequency range (Serman, Hannemann, &Kornagel, 2012).

A period of adaptation regardless of the technique used is required for realizing more benefits from such techniques. A large degree of individual variation can be expected. For reasons not fully understood, some people seem to benefit more than others. Children, perhaps because of much greater neural plasticity, seem to benefit more than adults (Ross, 2009).

The present study focused on evaluation of the effect of new technology in hearing aid, frequency compression on localization and speech identification in noise in individuals with sloping sensorineural hearing loss. The review has been into

2.1. Speech identification in noise

2.2. Localization.

2.1**. Speech identification in noise:**

Literature differs on the importance of frequencies above 2000 Hz for speech. In studying noise induced hearing loss, research has shown that thresholds at 3000 Hz and above are not significantly related to the hearing and understanding of everyday speech (Glorig, ward & Nixox, 1961; Quiggle, Glorig, Delk, & Summerfield, 1957). On the other hand, other researchers (Harris, Haines, & Myer, 1960; Kryter, Williams, & Green, 1962; Mullins & Bangs, 1957) have found that information in the frequencies above 2000Hz to be significant for understanding speech in the presence of noise. Pascoe (1975) suggested that the critical range of frequencies which have a significant effect on word recognition, particularly in noise, are those between 2500 and 6300 Hz.

Effect of sensorineural hearing loss in adults tend to have greatest amount of hearing loss in the higher speech frequencies (above 2000Hz), which generally corresponds to more extensive pathophysiological changes in the corresponding region of inner ear (Lieberman &Dodds, 1984; Willott, 1991). It is well established that in individuals with sensory neural hearing loss, suprasegmental features are perceived better than segmental features, vowels better than consonants, vowel height better than vowel position (front and back), word initial consonants better than word final consonants, and consonant voicing and continuance better than consonant place (Erber, 1972; Martony, Risberg, Spens, &Angelfors, 1972; Bilger& Wang, 1976; Hack &Eber, 1982).

Adult listeners with normal hearing seem to make more use of spectral cues for place of articulation information (Harris, 1958; Hedrick &Ohde, 1993; Heinz & Stevens, 1961; Hughes & Halle, 1965; Nittrouer, 2002; Zeng& Turner, 1090) and temporal information for the voicing distinction (Raphael, 1972; Cole & Cooper, 1975; Soli, 1982). Listeners with hearing impairment may have difficulty integrating amplitude and spectral cues, and may generally place less weight on formant transitions than listeners with normal hearing (Hedrick, 1997; Hedrick & Younger, 2003; Zeng& Turner, 1990).

Hogan and Turner (1998) evaluated the effects of hearing loss configuration and severity as well as the frequency bandwidth that maximized speech recognition scores. Speech recognition was tested at various band pass settings for five listeners with normal hearing and nine individuals with varying degrees of high frequency hearing loss. The test stimuli were presented through a Sennheiser HD 25-SP earphone with a supra-aural cushion. Results for the listeners with normal hearing demonstrated an increase in speech recognition scores as audibility increased. Results for the listeners with mild high frequency loss were similar to the listeners with normal hearing. Whereas results for listeners with moderate high frequency loss were poorer than those obtained from either the listeners with normal hearing or listeners with mild hearing loss.

Benefits of amplification were significantly more decreased when the degree of loss exceeded 55dB HL and the hearing loss fell in regions beyond 4 KHz as compared to when the hearing loss fell in regions below 5 kHz.(Augustana, 2001)

Overall results of various studies suggest that restoring of high frequency information to person with high frequency sensory neural hearing loss provides limited benefit to speech understanding. Based on these limited benefits, one recommendation may be to provide minimal or no amplification in some high frequency regions when greater hearing loss is present. There are a number of studies that make different claims about the effect of high frequency amplification. Byrne (1986) reported that listeners with sloping high frequency hearing loss judged the amplification providing the most extended high frequency emphasis to be the poorest in intelligibility. Most of the hearing instruments used in the study failed to amplify beyond 3 kHz.

Sullivan, Allsman, Nielsen, and Mobley (1992) speculated the increase in speech recognition for listeners with flat configurations was contributed to greater gain in the high and mid frequencies rather than simply amplification beyond 3 kHz. Without amplification, listeners with sloping losses were already receiving the maximum mid-frequency speech cues plus some high frequency speech cues. With amplification, listeners received only additional high frequency speech cues which resulted in little to no improvement in speech recognition scores. Without amplification, listeners with flat configurations received some mid frequency and high frequency speech cues. With amplification, listeners with flat configurations received additional mid frequency and high frequency speech cues which resulted in a significant improvement in speech recognition scores. Stated differently, with amplification, listeners with sloping losses were receiving high frequency speech cues, whereas, listeners with flat loses were receiving speech cues in the high frequencies as well as the low to mid frequencies. Therefore, Sullivan, Allsman, Nielson, and Mobley (1992) concluded that studies suggesting speech recognition scores improved due to high frequency amplification are questionable.

The management for individuals with sloping high frequency hearing loss is a challenging task. The conventional solution for individuals with a sloping audiometric pattern is a hearing aid with a frequency-gain response that improves audibility of high-frequency speech cues. However, even within a given frequency band, speech levels vary by at least 30dB (Fletcher, 1955; Skinner, 1988). This range is considerably increased by the variety of sound levels in different listening situations. For listeners with sloping loss, this variation is speech levels, couples with a reduced high-frequency dynamic range, may limit the ability to restore audibility without discomfort or distortion from higher level speech.

2.2 Localization:

According Flamme (2002), regarding localization the primary problem seen with is long delay times is destructive interference between the acoustic signal that passes by the hearing aid and the amplified sound. For some amounts of delay, the interference could move into frequency regions where the audibility of localization cues is reduced. The delay times might not be bilaterally matched, either because of a unilateral fitting or because of mismatched delays for bilateral hearing aid users. However, if the mismatch in delay time does not change often, people adapt to new interaural time difference cues over a period of hours or days.

Perreau, Bentler, and Tyler (2013) studied the contribution of a frequency-compression hearing aid to contralateral cochlear implant performance. The first experiment investigated the contribution of a frequency-compression hearing aid to contralateral cochlear implant (CI) performance for localization and speech perception in noise. The second experiment assessed monaural consonant and vowel perception in quiet using the frequency-compression and conventional hearing aid without the use of a contralateral CI or hearing aid. Ten subjects fitted with a cochlear implant and hearing aid participated in the first experiment. Seventeen adult subjects with a cochlear implant and hearing aid or two hearing aids participated in the second experiment.Histories of post lingual deafness were taken of a moderate or moderate-to-severe hearing loss who were not used to frequency-lowering hearing aid previously. In the first experiment, performance using the frequency-compression and conventional hearing aids was assessed on tests of sound localization, speech perception in a background of noise, and two self-report questionnaires. In the second experiment, consonant and vowel perception in quiet was assessed monaurally for the two conditions. In both experiments, subjects alternated daily between a frequency-compression and conventional hearing aid for 2 months. The parameters of frequency compression were set individually for each subject, and audibility was measured for the frequency compression and conventional hearing aid programs by comparing estimations of the Speech Intelligibility Index (SII) using a modified algorithm (Bentler et al., 2011). In both experiments, the outcome measures were administered following the hearing aid fitting to assess performance at baseline and after 2 months of use. Results revealed that no significant difference between the frequency-compression and conventional hearing aid on tests of localization and consonant recognition. Spondee-in-noise and vowel perception scores were significantly higher with the conventional hearing aid compared to the frequency-compression hearing aid after 2 months of use. These results suggest that, for the subjects in their study, frequency compression is not a better bimodal option than conventional amplification. In addition, speech perception may be negatively influenced by frequency compression because formant frequencies are too severely compressed and can no longer be distinguished.

Multichannel compression amplification offers an attractive option for improving speech audibility in listeners with sloping loss. When speech varies over a range of input levels, the compression can improve recognition by placing greater amounts of the speech signal in the range between threshold and discomfort (Moore &Glasberg, 1986; Souza & Turner, 1998). Use of more than one compression channel allows the audiologist to maximize audibility by accommodating variations in threshold and dynamic range across frequency. However, maximizing audibility in the regions of greater loss (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998).

To overcome the difficult, that most of the individuals with hearing loss have poorer thresholds at the high frequencies when compared to low frequencies had led to the development of Frequency lowering technology, the main objective is to make use of better thresholds at lower frequencies to improve the audibility of high frequency information hearing components of speech. The information conveyed by the high frequency may be perceived as a lower frequency substitute. The addition of this information, along with the intact low mid frequency information, should improve the audibility of sounds for individuals using transposition device over conventional amplification (Kuk, Keenan, Peeters, Korhonen, Hau, & Anderson, 2007).

It is possible that frequency lowering can improve the ability of some listeners to perceive details of spectral shape, perhaps resulting in better speech intelligibility. This benefit may be obtained if the broadening of auditory filters, which usually accompanies sensory neural hearing loss, is not as extensive at low frequencies as at high frequencies.

Main types of frequency lowering technology:

Frequency transposition: the basis of this is the high frequency signal is transposed or moved down to some other frequency region where it is more able to analyze signal. By providing a representation of high frequency sounds which would otherwise be inaudible, it is anticipated that improvements may occur in speech perception and intelligibility in individuals with high frequency sensory neural hearing loss as it provided additional cues for the discrimination of speech. When the right candidates are chosen and when specific guidelines are followed, frequency transposition provides a viable solution for adults and children with an unaidable hearing loss in the high frequencies (Kuk, Keenan, Peeters, Korhonen, Hau, & Anderson, 2007).

In frequency compression signal processing strategy, there is proportional compression of high frequency signal into lower frequency ranges by reducing the bandwidth and frequency of the signal. Proportional frequency compression attempts to preserve the relationship of the high frequency energy peaks while leaving low frequency information uncompressed but amplified. For these users both the hearing level at specific frequencies and the slope of the audiogram across frequencies are taken into account. for cut-off frequency, relatively high frequencies are selected, if the hearing impairment is mild or the audiogram is flat. The lower cut-off frequencies are selected for more severe levels of impairment or for audiograms with relatively steep slopes. The higher the degree and steepness of hearing loss, lesser the cut off frequency and more is the degree of frequency compression that is applied.

Studies have shown that Non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses. (Simpson et al., 2006; Bohnert, Nyfellar, &Keilmann, 2010). McDermott et al. (1999) examined performance in a group of five adults fit monaurally with the same FC device. In a 12 week period, it was noted that the FC did significantly improve the recognition of HF phonemes for two of the five individuals. However for two individuals, sentence test results were significantly improved over their own hearing aids not because of the frequency lowering but because of the low frequency amplification.

McDermott and Knight (2001) reported that consonant identification scores were the same for the Linear frequency transposition (LFT)-on and the LFT-off conditions. However, a significant improvement in consonant identification scores was obtained after training.

Swapna and Rajalakshmi (2007) studied the efficacy of frequency transposition hearing aid in subjects with dead regions. In the study, it was found that with frequency transposition there was significant amount of benefit than without it. Hrishikesan and Manjula (2009) studied the efficacy of non linear frequency compression in individuals with and without cochlear dead regions. The results revealed that there was a significant difference in the mean SIS scores without NLFC and NLFC fine tune setting for individuals without cochlear dead region. There was no significant difference in individuals with cochlear region ling's six sound identification reveal a slight improvement in fricative identification among participants without cochlear dead region only. The results of quality rating showed that the mean rating of quality were higher for individuals without cochlear region compared to those with cochlear dead region.

Anjana and Geetha (2011) studied the utility of non linear frequency compression on detection and speech identification abilities in quiet and in presence of noise, in children with severe to profound hearing loss who have limited or no benefit from high frequency amplification. Results revealed NLFC benefits for detecting high frequency tones. Identification of words also showed significant benefit from NLFC in quiet and in the presence of noise.

As there are evidences regarding the usefulness of high frequency amplification in individuals with high frequency sensorineural hearing loss, there is a need to validate the effect of frequency compression on speech identification in noise and on localization.

CHAPTER 3

METHOD

The present study focused on evaluating the effect of frequency compression on speech perception in noise and on localization in individuals with sloping sensorineural hearing loss, under two aided conditions - without frequency compression and with frequency compression.

Participants

The present study incorporated 20 ears of 10 individuals with bilateral sloping sensorineural hearing loss. The slope considered was gradual 10 – 15 dB per octave from 2 k Hz. The participants were native speakers of Kannada in the age range from 15 to 55 years. The degree of hearing loss ranged from moderately severe to profound sensorineural hearing loss. All participants were naive hearing aid users, except two who were experienced hearing aid users. There participants were not having any middle ear pathology as revealed by immittance evaluation. Further, participants with any complain of neurological or cognitive problems were also excluded from the study.

Test material

The Phonemically Balanced Word list (Yathiraj&Vijayalakshmi, 2005) and high frequency word list (Mascarenhas, 2001) were used for speech identification. The PB word list consisted of four lists of 25 bi-syllabic words each. The high frequency word lists consisted of three lists with words having speech sounds predominantly above 2 kHz. Thirty-two trains of white noise burst were used to evaluate the localization ability.

Instrumentation

A calibrated diagnostic sound field audiometer (MADSEN, ORBITER, 922) was used to administer pure-tone audiometry, speech audiometry and aided performance. A calibrated immittance meter (GrasonStadler Incorporated Tympstar) was used for ruling out middle ear pathology. Two digital BTE hearing aids with 6 channels, Sound Recover feature (Frequency compression between 1.5 kHz to 6 kHz), gain of 80 dB SPL, MPO of 141 dB SPL were used. The HiPro connected to a personal computer with NOAH software and default hearing aid programming software was used to program the hearing aid.

For localization eight loudspeakers connected to a personal computer with CuBase 6 software was used. The loud speakers (Genelec 8020B speakers) were mounted on Iso-Pod™(Isolation position/decoupler™) vibration insulating table stand and were located at 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, and 315^o Azimuth covering a range of 0^o to 360^o. The loud speakers were arranged in a circular array with one meter radial diameter from centre.

White noise stimulus generated using Adobe Audition 3.0 on the computer was routed through these speakers. The output of each loud speaker was calibrated using a Larson-Davis system 824 Sound Level Meter (model no. 2540) placed at centre with a ½ inch free-field microphone. The microphone of the sound level meter with preamplifier was placed at a position corresponding to the centre of the head and at a height of one meter. The sound pressure level readings were taken by presenting the noise burst stimuli of 30 second duration through each of the loudspeakers.

Hearing aid programming

The data for the present study were collected in aided condition. The test hearing aids were programmed by connecting them to the HiPro which in turn was connected to the personal computer with software for hearing aid programming. The hearing aid was programmed using the auditory thresholds of the participants and the proprietary fitting formula. Audibility of Ling's six sounds was done for optimization of the gain provided to each ear of each participant.

Two programs were enabled for each ear, Program 1 was set with frequency compression (FC) feature disabled, and Program 2 was set with frequency compression (FC) enabled.

Procedure

All the testing was carried out in an air-conditioned sound treated single or double room set-up. The data were collected in two phases. Phase I included collection of data on speech identification in noise (SNR-50) in monoaural aided condition. Phase II included collection of data on localization in binaural aided condition.

Phase I.

This stage incorporated measurement of speech identification in Noise (SNR-50).The task was to measure the speech identification in the presence of noise through the SNR-50 measure. This was done in the aided condition without and with FC. The participants were instructed to repeat the words presented in the presence of noise. They were also informed that the level of speech would remain constant and that of noise would be varied.

The participant was made to wear the hearing programmed aid on the test ear coupled using an eartip. The hearing aid was set to P1 and later changed to P2 program setting. He/she was seated on ca chair comfortably in the patient room, at a distance of one meter and an angle of 0^0 Azimuth from the loudspeaker. The PB words list (Yathiraj&Vijayalakshmi, 2005) was presented in live mode by a native Kannada speaker at 45 dBHL, with VU monitoring.

Signal to noise ratio-50 (SNR-50) was used to measure the speech identification in noise performance. For the measurement of SNR-50, the level of speech was kept constant at 45 dB HL. The initial level of speech noise was 30 dB HL. The level of noise was increased initially in 5 dB steps (later in 2 dB steps) till the participant repeated 50%

of the words being presented. Three words were presented at each level of speech noise. This was done to find out the highest level of speech noise at which the participant could repeat 50% of the words. At this point, the difference in the level of speech and speech noise was noted as the SNR-50.The above procedure was used to measure the SNR-50 for PB word list and HF word list (Mascarenhas, 2001), in two aided conditions (without and with FC).

Phase II.

This stage consisted of localization experiment. The task was to point to the direction from where the noise burst was presented. The noise burst stimuli was presented randomly four times with an inter stimulus interval of 5 seconds. The noise bursts were presented from each of the eight loud speakers located at different azimuths, from 0^{o} to 360^{o} A at 45^{o} intervals.

The participant was seated at the centre, i.e., equidistant from the eight loud speakers. The participants were instructed to point to the loud speaker from where they hear the train of noise burst. A set of stimuli for localization consisted of 32 trains, each train consisted of 4 white noise bursts. The response of the participant was noted in terms of the loud speaker from which he/she thought that the sound arrived with respect to the loud speaker through which the sound was actually presented. The difference between the target loud speaker and the response was utilized to compute the degree of error (DOE) for localization.

The DOE corresponds to the difference in degrees between the degrees of azimuth of the loudspeaker of actual presentation of the stimuli, to the degree of azimuth of the loudspeaker identified as the source of the stimulus by the participant. For example, if the stimulus was presented from a loudspeaker at 45^{0} azimuth and the participant reported the sound to be arriving from loudspeaker at 315^{0}, then the degree of error would be 90^0 i.e., 45^0-(315^0) = 90^0. This DOE was obtained for 8 trials in each aided condition. Thus, in each of the two aided conditions, there was a set of eight degrees of errors. The formula for calculating the root mean square DOE (Ching, Incerti, & Hill, 2004) is given below.

$$\text{rms DOE} = \sqrt{\frac{(DOE)_1^2 + (DOE)_2^2 + (DOE)_3^2 + \ldots + (DOE)_8^2}{8}}$$

Where, DOE_{1-8}= Degree of Error of the eight loud speakers; and

rms DOE = Root mean square degree of Error.

This procedure was used to measure the localization in two aided conditions, without FC and with FC. For each participant, the DOE for localization from each loud speaker, Front (0^o, 45^o and 315^o), back (135^0, 180^0 and 225^0), right (45^0, 90^0 and 135^0) and left (225^0, 270^0 and 315^0) localization were also computed. This was done by averaging the DOE for corresponding number of loud speakers.

In the present study, for each test ear, the SNR-50 was obtained. In addition, for ear individual, DOE of localization for eight loud speakers, front, back, right and left loudspeakers were obtained. The data were tabulated subjected to statistical analysis using Statistical Package for Social Sciences statistics 17 (SPSS). Descriptive statistics and Analysis of variance using non-parametric statistics were carried in order to find out the effect of frequency compression on SNR-50 and localization.

CHAPTER4

RESULTS AND DISCUSSION

The study was conducted with the aimof evaluating the effect of frequency compression (FC) in hearing aids on speech identification in noise (SNR-50) and localization, in individuals with sloping sensorineural hearing loss.

The data collected on SNR-50 (for PB and high frequency words) and localization in two aided conditions (i.e., without frequency compression and with frequency compression) were tabulated and analyzed using Statistical Package for Social Sciences version 17 (SPSS). The statistical tools used to measure are descriptive statistics and analysis of variance.

The data were collected from 10 individuals with sloping sensorineural hearing loss. The parameters measured were SNR-50 for speech perception in noise, and root mean square degree of error (rmsDOE) for localization.

The results are discussed under the following headings:

4.1 SNR-50

4.2 Localization.

4.1 SNR-50 for Phonemically Balanced (PB) words and High Frequency (HF) words:

The mean and standard deviation (SD) of SNR-50 collected from 20 ears (10 right and 10 left) of 10 subjects for phonemically balanced and high frequency words are provided in Table 4.1.

Table 4.1

Mean, median and standard deviation (SD) of SNR-50 for PB words and HFwords.

Ear	*Aided condition*	*SNR-50 in dB*					
		PB words			*HF words*		
		Mean	*Median*	*SD*	*Mean*	*Median*	*SD*
Right	Without FC	1.60	2.0	2.12	4.7	4.0	3.47
(N=10)	With FC	-1.30	-2	2.06	-1.4	-2.5	2.55
Left	Without FC	2.50	3	3.14	3.4	3.5	2.91
(N=10)	With FC	-0.5	-1.5	2.95	-2	-2.5	2.87

Note: 'dB': Decibel; 'PB': Phonetically Balanced; 'HF': High Frequency; 'SD': Standard Deviation; 'FC': Frequency Compression; 'N': Number of subjects

From Table 4.1 and Figure 4.1, it can be noted that the mean SNR-50 was lower in the aided condition with frequency compression indicating better performance in this condition, compared to the condition without the FC.This means that the performance is better in the aided condition with FC since the participants repeated 50% of the words even when the difference between the speech and speech noise was lesser. Further, the performance for the PB words was better compared to the HF words. The median values are also depicted in the tableas the standard deviation values indicated high variability.

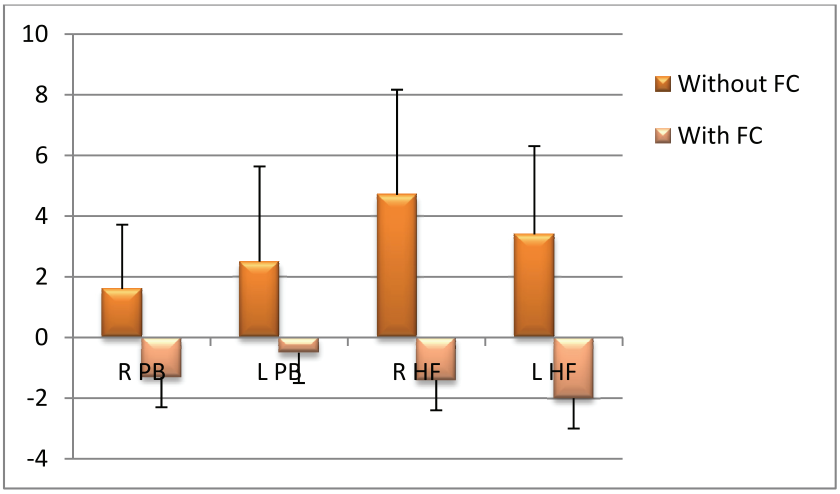

*Figure 4.1.*Box plot of mean and standard deviation of SNR-50 for PB words and words in right and left ears, without frequency compression (FC) and with frequency compression (FC)

The Wilcoxon signed ranks test was performed inorder to see if there was a significant difference in SNR-50 between the right ear without FC and left ear without FC, and between the right ear with FC and left ear with FC. This was done with an intention of grouping the right and left ear scores if there was no significant difference between their scores.

Table 4.2

Results of Wilcoxon's signed rank test for right and left ear SNR-50 values

	SNR-50			
Aided Conditions	*PB Words*		*HF words*	
	Z	*P*	*Z*	*P*
Right-Left (Without FC)	-1.022	0.307	-0.921	0.357
Right-Left (With FC)	-1.14	0.254	-1.027	0.305

Note: 'HF': High Frequency; 'SD': Standard Deviation; 'FC': Frequency Compression; 'N': Number of subjects

The test revealed that there was no significant difference between the right and left ears in the two aided conditions (i.e., without and with FC). Hence, the SNR-50 values of the right and left ears were grouped together, for the two aided conditions. Table 4.3 and Figure 4.2 provide the mean, median and SD of the SNR-50 for PB and HF words when the SNR-50 valuesof the two ears were combined, in the two aided conditions.

Table 4.3

Mean, median and SD of SNR-50 (in dB) for PB and HF words, in the two aided conditions (without FC and with FC).

Aided Conditions (N=20)	*Stimuli*	*SNR-50 in dB*		
		Mean	*Median*	*SD*
Without FC	PB words	2.05	3.00	2.37
	HF words	4.05	5.00	2.78
With FC	PB words	-0.90	-1.25	2.25
	HF words	-1.70	-2.00	2.59

Note: ‘dB’: Decibel; ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘SD’: Standard Deviation; ‘FC’: Frequency Compression; ‘N’: Number of subjects

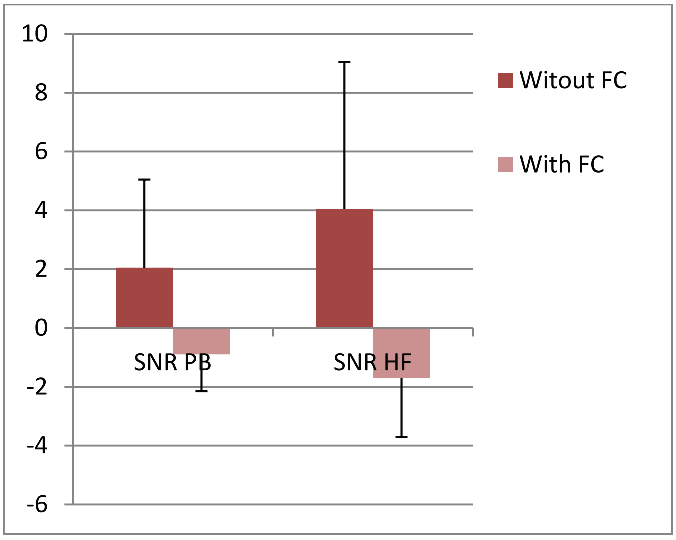

Figure 4.2. Box plot showing the mean and SD of SNR-50 for PB and HF words in the two aided conditions

From the Figure 4.2, it can be noted that the performance for both PB and HF words was better in the aided condition with FC compared to without FC. To examine if this difference in the aided conditions was significant, Wilcoxon's signed ranks test was done. This test (Table 4.4) revealed that there was no significant difference between the SNR-50 in the two aided conditions (without FC and with FC), for both PB and HF words.

Table 4.4

Results of Wilcoxon's signed rank test for SNR-50 values in the two aided (without FC and with FC) conditions

AidedConditions	*SNR-50*			
	PB words		*HF words*	
	Z	*p*	*Z*	*p*
Without FC –With FC	-2.494	0.013	-2.810	0.005

Note: 'PB': Phonetically Balanced; 'HF': High Frequency; 'FC': Frequency Compression;

From Tables 4.3 and 4.4, it is evident that the SNR-50 performance was significantly better in the aided condition with FC compared that condition without FC. Hence, it can be inferred that the FC provides benefit in speech understanding in the presence of noise.

In literature, there are reports stating that frequency compression does not make a difference in performance compared to conventional amplification (Anna, Ingrid, Hartley, Lisa, Gitte, &Myriel, 2010) or that the frequency compression improves performance (Simpson et al., 2006); Bohnert, Nyfellar, & Keilmann,2010; McDermott et al., 1999). There are reports which support the results of the present study.

Simpson et al. (2006), Bohnert, Nyfellar, and Keilmann (2010) have shown that non-linear frequency compression (NLFC) has been found to be beneficial for speech identification in presence of noise in sloping hearing loss as well as severe to profound losses. McDermott et al. (1999) noted that the FC did significantly improve the recognition of HF phonemes for two of five individuals who were fittedwith FC devicemonaurally, when evaluated after a 12 week period. Swapna and Rajalakshmi (2007) found that there was a significant benefit with frequency transposition than without it, in subjects with dead regions. Hrishikesan and Manjula (2009)have also found significant better performance on speech identification with non-linear frequency compression (NLFC),in individuals without cochlear dead region. They also noted that the performance was better when the NLFC was optimized for individual participant. Anjana and Geetha (2011) obtained NLFC benefits for detecting high frequency tones. Identification of words also showed significant benefit from NLFC in quiet and in the presence of noise.

4.1 Localization

Localization in horizontal plane was measured at eight azimuths, i.e., 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o with the participant wearing binaural hearing aids, in FC enabled and disabled conditions. The root mean square degree of error (rmsDOE) is calculated for each angle that was included in the study 0^o, 45^o, 90^o, 135^o, 180^o, 225^o, 270^o, 315^o. Further, the rmsDOE was also compared for right, left, front, back and overall localization were also evaluated.

Table 4.5

Root mean square degree of error (rmsDOE) in localization of eight different angles.

Aided Condition	*Stat measure*	*rmsDOE* 0^0	45^0	90^0	135^0	180^0	225^0	270^0	315^0	*Overall*
Without FC	Mean	60.75	21.38	36.0	40.25	1.13	37.13	11.25	3.37	40.96
	Median	56.25	11.25	11.25	32.50	0	22.50	5.63	0	31.57
	SD	49.52	25.13	43.67	34.92	6.39	58.59	19.12	15.95	24.81
With FC	Mean	48.38	9.00	7.88	25.88	0	5.63	2.25	2.25	25.72
	Median	33.75	5.63	0	11.25	0	11.25	0	0	24.19
	SD	56.39	13.83	21.89	27.07	0	10.93	24.19	32.17	22.33

Note: ‘dB’: Decibel; ‘PB’: Phonetically Balanced; ‘HF’: High Frequency; ‘SD’: Standard Deviation; ‘FC’: Frequency Compression; ‘N’: Number of subjects

From Table 4.5, it can be observed that in the aided condition without FC, the rms DOE was highest at 0^0 followed by 135^0, 225^0, 90^0, 45^0, 270^0, 315^0 and 180^0. In the aided condition with FC too, a similar pattern was noted except at $45^0$and 225^0. Figure 4.3 also depicts the same.

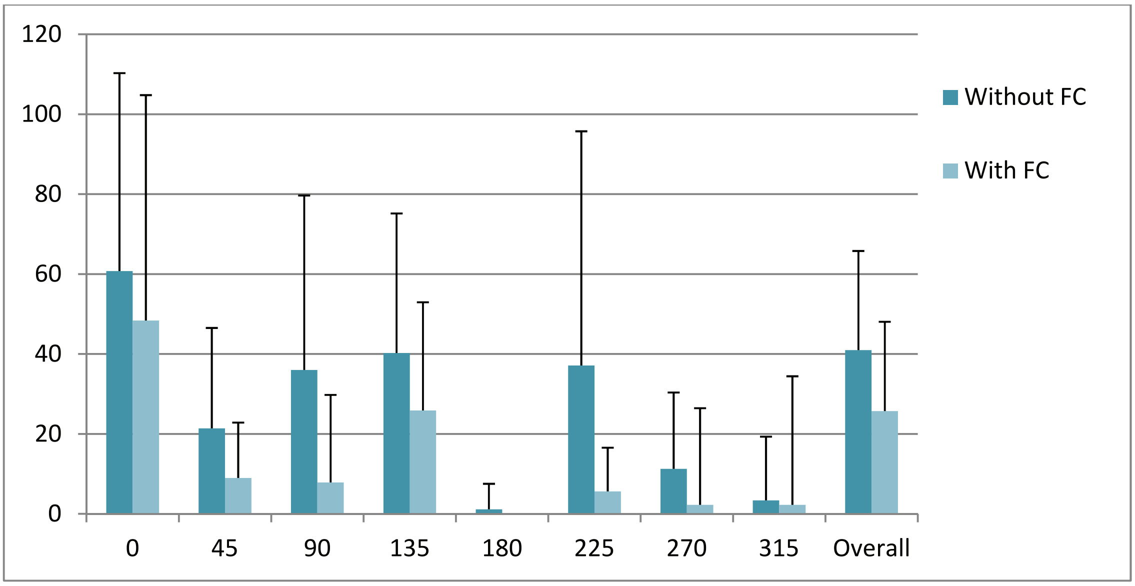

Figure 4.3 Box plot of mean and SD of the rms DOE without FC and with FC, at eight different angles

The rmsDOE were higher in the aided condition without FC compared to with FC condition, indicating that localization was facilitated by FC in the hearing aid. This could be because, the high frequency audibility was increased with FC compared to without FC condition. In order to know if there was a significant difference between without FC and with FC conditions, Wilcoxon signed ranks test was administered. This revealed that there was a significantly better performance with FC compared to without FC at 0^0, 45^0, 90^0, 135^0, and 225^0angles (Table 4.6). The overall localization ability (mean performance of eight different angles) was also significincly better with FC compared to without FC condition.

Table 4.6.

Results of Wilcoxon Signed Ranks test for localization of eight angles for two conditions.

Angles in Degrees	*Z*	*p*
0	-1.261	0.207
45*	-2.456	0.014
90*	-2.414	0.016
135*	-2.032	0.042
180	-.577	0.564
225*	-2.201	0.028
270	-1.276	0.202
315	.000	1.000
Overall*	-2.803	0.005

Note: *: significant difference at 0.05 level

The mean and SD of root mean square degree of error in the horizontal plane localization from front, back, right and left is given in Table 4.7. It can be observed that in the aided condition without FC, the rms DOE was highest at right followed by front, back and left sides. In the aided condition with FC too, the rms DOE was the highest from front followed by right, back and left. Figure 4.4 also depicts the same. Further, the variability in rmsDOE was in higher without the FC condition as revealed by the SD.

Table 4.7.

Mean, median and SD of rms DOE in front, back, right and left localization

Aided Conditions		*Localization*			
		Front	*Back*	*Right*	*Left*
Without FC	Mean	28.50	26.17	32.54	17.25
	Median	24.38	15.0	26.25	7.5
	SD	28.41	26.03	30.97	26.29
With FC	Mean	15.0	7.13	13.88	1.13
	Median	7.5	1.88	7.5	3.75
	SD	31.62	11.79	18.20	18.63

Note: 'SD': Standard Deviation; 'FC': Frequency Compression; 'N': Number of subjects

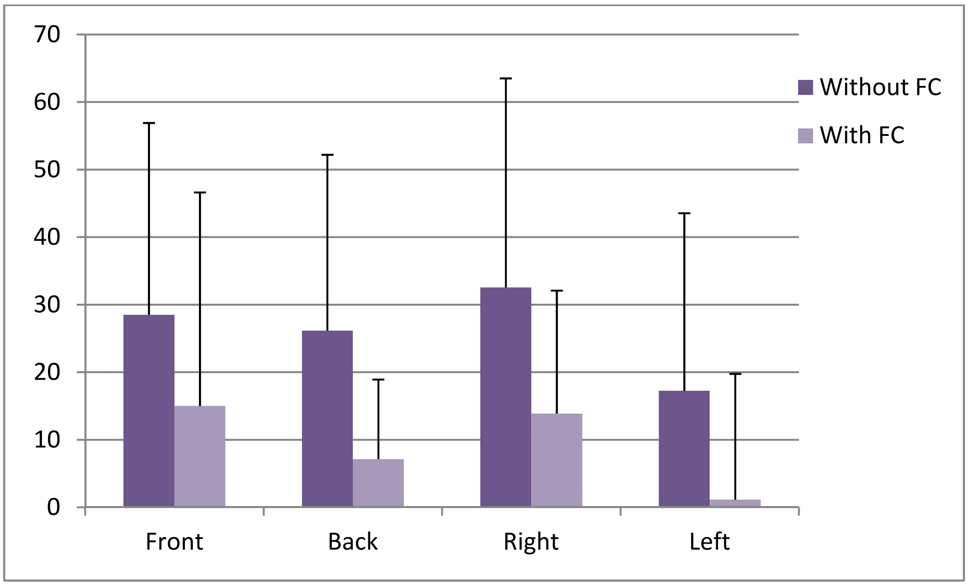

*Figure 4.4.*Box plot of mean and SD of the rms DOE in localization of front, back,right and left sides, without FC and with FC

Further, the rms DOE were higher in the aided condition without FC compared to with FC condition, indicating that the localization was facilitated by FC in the hearing aid. In order to know if there was a significant difference between the without FC and with FC conditions, Wilcoxon signed ranks test was administered(Table 4.8). This revealed that there was a significantly better performance with FC compared to without FC at all directions, i.e., front, back, right and left. The overall localization ability (mean performance of eight different angles) was also significantly better with FC compared to without FC condition. This is because thefrequency compression increases the audibility of high-frequency localization cues.

Table 4.8.

Wilcoxson test result for significant difference between with and without FC conditions

Localization with and without FC	*Z*	*P*
Front	-2.655	0.008
Back	-2.451	0.014
Right	-2.670	0.008
Left	-2.103	0.035
Overall	-2.803	0.005

Note: ‘FC’: Frequency Compression

There are limited studies on localization using frequency compression technology. In the present study, it could be inferred that frequency compression helps in improving the performance on localization. The FC facilitated the audibility of high frequencies to a significant extent that the localization improved with FC compared to without FC. However, in the study by Anna, Ingrid, Hartley, Lisa, Gitte, and Myriel(2010), it was reported that there is no significant difference in localizationwith frequency compression ‘on’and‘off’ condition.The explanation provided by them was that though frequency compression increased audibility of monaural high-frequency front-back localization cues between 2000 and 5000 Hz, that they were spectrally compressed may have made them less usable.

The results reveal that better performance was observed in aided condition with FC enabled on speech identification in noise(SNR-50) for PB words & HF words andonlocalization (rmsDOE).

CHAPTER5

SUMMARY AND CONCLUSIONS

The present study focused on evaluating the effect of frequency compression on speech identification in noise and on localization in ten individuals with sloping sensorineural hearing loss, under two aided conditions - without frequency compression and with frequency compression (FC).

The study was conducted in two phases. In Phase I, Speech identification in noise (SNR-50) was measured and in Phase II, localization for eight angles was evaluated. The data collected on speech identification in noise, SNR-50 (for PB and high frequency words) and localization in two aided conditions (i.e., without FC and with FC) were tabulated and analyzed using Statistical Package for Social Sciences version 17 (SPSS). The statistical tools used to measure are descriptive statistics and analysis of variance. The results revealed that:

1. There was no significant difference in SNR-50 between the right and left ear in the two aided conditions (without FC and with FC). Hence, the data from the two ears were grouped together.
2. The speech perception in noise was better in the aided condition with FC enabled than when it was disabled. This was true for both PB words and HF words.
3. The benefit obtained from FC for HF words was more than for PB words, indicating that high frequency audibility was improved with FC.
4. In localization, the degree of error was less when the FC was enabled than when it was disabled. This could again due to the fact that the high frequency audibility improved with FC. There was significantly better

horizontal plane localization for front, back, right and left in with FC compared to without FC condition.

It could be inferred from the results of the present study that the performance is better, in both speech identification in noise and localization, in the aided condition with FC enabled.

Clinical implications of the findings of the present study is that frequency compression in hearing aids helps an individual with sloping hearing loss to understand speech in noise and in localization.

Future directions for research:

a. This study can be further extended to find out the effect of frequency lowering more number of participants.
b. Further, this study can be extended to compare between conventional hearing aid and frequency lowering technology.

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